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**SYMPOSIUM ON FLOODS
SECTION OF HYDROLOGY**

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SYMPOSIUM ON FLOODS

INTRODUCTION

Merrill Bernard

The Commission of Potamology of the International Association of Scientific Hydrology has selected as one of its topics, or questions, to be presented at the Seventh Assembly of the International Union of Geodesy and Geophysics the following:

"Question 2: The forecasting of floods, with special regard to observations of rainfall, of snow-cover, and of atmospheric conditions, and, if possible, weather-forecasts. Concrete examples of practical application."

The forecasting of floods may be considered as embracing the development and application of methods of predicting the arrival of an impending flood. Or the subject may be broadened to encompass a wider field of interest in floods including the social and economic phases of their control and disposition. Flood-forecasting and flood-control are inherently related--flood-forecasting becoming essential to the design and operation of control-works; flood-control making possible the fullest utilization of our richest valleys and flood-plains.

It is felt that the answer to Question 2, for the United States, should reflect the views of those who, among others, have contributed to a rapidly growing knowledge of the flood-phenomenon and that the broader view of the problem as outlined in the question should be taken.

Accordingly, the hydrology of floods and the place of flood-control in national water and land-use policy has been discussed, together with the more practical problems of applying hydrologic research to the organization of forecasting services and to engineering design.

The contributing authors and their subjects are as follows: Thorndike Saville, "Trends in a National policy of stream-management"; Gerard H. Matthes, "Flood-data in the United States"; Clarence S. Jarvis, "Great floods in the United States"; W. G. Hoyt and Walter B. Langbein, "Some general observations of physiographic and climatic influences on floods"; LeRoy K. Sherman, "Recent advances in applied hydrology with reference to flood-forecasting"; Carl G. Paulsen, "The measurement and computation of flood-discharge"; Merrill Bernard, "Recent developments in flood-forecasting"; George D. Clyde, "Stream-flow forecasting by snow-surveying"; Gail A. Hathaway, "Estimating maximum flood-flow as a basis of the design of protective works"; Arthur C. Ringland, "The relation of headwaters-control to the National program of flood-protection"; H. R. Byers, "The meteorological phase of flood-forecasting"; R. T. Zoch, "The mathematical synthesis of the flood-hydrograph"; and Gilbert F. White, "Economic aspects of flood-forecasting."

U. S. Weather Bureau,
Washington, D. C.

TRENDS IN A NATIONAL POLICY OF STREAM-MANAGEMENT

Thorndike Saville

Quite aside from the distinction of this program as attested by the scientific character of the papers and the eminence of the speakers who are to follow me, it seems clear that your Reporter is determined to make this occasion unique in yet another way. I refer to his originality in proposing that a Symposium on Floods should be inaugurated by a paper dealing with the general subject of stream-management. From time to time there have appeared in the engineering literature of this country, and I dare say in that of other countries also, reports of symposia on various aspects of water-control and use, such as floods, droughts, pollution, power, navigation, etc. That these important subjects are inextricably related hydrologically, economically, and socially must be apparent, but in technical discussions such considerations have heretofore been conspicuous by their absence or by the cursory attention accorded them. Man does not live to himself alone, neither does the hydrologic cycle revolve only around flood-phenomena. It is gratifying to realize that in your deliberations upon various scientific aspects of floods and flood-control, you propose to retain a broad perspective with relation to other factors affecting the use and regulation of water.

In this country a National policy of stream-management will differ radically from that

likely to prove effective in most other countries. This arises from the peculiarities in the relationships between the Federal and the State governments. The Federal Government performs its undertakings by virtue of a series of enumerated powers granted in the Federal Constitution. The Constitution reserves to the States all powers not delegated by it to the United States Government. Since the conservation or control of water is nowhere specially enumerated as a Federal responsibility, such measure of jurisdiction as the Federal Government may exercise in these spheres of activity rests upon the interpretation of certain broad phrases in the Constitution.

All acts of the Federal Government relating to the development and control of the water-resources of the nation which have been tested in the Supreme Court have been based upon either the "Commerce Clause" or the "Territories Clause" of the Constitution. The first states that "The Congress shall have power to . . . regulate commerce with foreign nations and among the several States," and the second that "The Congress shall have power to dispose of and make all needful rules and regulations respecting the Territory or other property belonging to the United States."

Practically from the inception of the United States, the improvement of its waterways in the interest of navigation has been an admitted Federal responsibility under the Commerce Clause, and such improvements have been carried out by the Corps of Engineers of the War Department.

For many years until the beginning of the Twentieth Century the participation of the Federal Government in water-undertakings was largely confined to bona fide improvements of navigation. Meanwhile the States were developing various policies with respect to control of waters, the common-law riparian doctrine generally holding in the States east of the Mississippi and the doctrine of prior appropriation being established in most of the arid and semiarid western States. The general law with respect to the rights of a State in the control of its waters has been laid down by the Supreme Court of the United States to the effect that a State may adopt any policy it wishes with respect to ownership and control of its streams except that it is subject to the following limitations [United States vs. Rio Grande Dam and Irrigation Co. (174 U.S. 690-703)]:

"First, that in the absence of specific authority from Congress a State cannot by its legislation destroy the right of the United States, as the owner of lands bordering on a stream to the continued flow of its waters; so far at least as may be necessary for the beneficial uses of the Government property.

"Second, that it is limited by the superior power of the General Government to secure the uninterrupted navigability of all navigable streams within the limits of the United States."

In a democracy, particularly one like ours in which the powers of the Federal Government have been delegated to it by the States which retain to themselves those elements of sovereignty not so delegated, it is not surprising that National policies relating to natural resources should be only slowly evolved. The vast extent of the nation, with major differences in the character of problems pertaining to the use and control of such resources and the changing concepts with respect to private and public rights in their administration and regulation, have further complicated the evolution of either comprehensive or fixed National policies. The past decade has not only witnessed a resurgence of the public concern for conservation of our National resources which was born in the days of Theodore Roosevelt, but has been distinguished by profound changes in concepts of Federal responsibility and Federal participation in costs. It is necessary, therefore, in discussing trends in a National policy of stream-management, to refer more or less chronologically to the principal Acts of Congress dealing with water-conservation and control and to attempt to indicate from them the means by which a Federal water-policy is slowly being evolved

(1) Navigation

In 1894 Congress passed an Act by which authority was given to the Secretary of War to issue regulations governing the use and administration of navigable waters. This was the first Federal Act relating to the control or administration of water-resources in the United States. On March 3, 1899, Congress passed the so-called "Dam Act" which, as amended by Acts of June 21, 1906, and June 23, 1910, provided that the specific approval of Congress must be received before dams, bridges, or other structures were placed in or across navigable waterways. The conditions imposed by these Acts ultimately were largely responsible for the passage of the Federal Power Act later, since on the one hand so much political maneuvering and delay was required to get an Act of Congress authorizing the construction of an important dam, bridge, or other necessary structure, and on the other hand public opinion was becoming aroused over exploitation of the natural resources of the country by private interests.

By Acts passed in 1906 and 1910 Congress delegated authority to the Chief of Engineers and to the Secretary of War to impose regulations with respect to the construction of dams which might affect navigation. It was under these Acts that the Engineer Corps of the War Department began to exercise the powers which have grown so tremendously in later years.

(II) Navigation and deposits in streams

In 1893 Congress passed the California Debris Act. This created a Commission under the control of the Army Engineers to which was delegated the power of regulating hydraulic mining in California in the interest of navigation. This Act marked an important departure from regulatory powers of the Federal Government exercised previously solely on navigable streams, since the major activity to be regulated by this Act, namely, hydraulic mining, existed on non-navigable streams which were tributary to navigable streams. However, a decision by the Supreme Court of the United States upheld the constitutionality of the Act on the score that it was clearly demonstrated to be essential to maintain navigation on the Sacramento River.

The River and Harbor Act of March 3, 1899, as amplified by a similar Act of March 3, 1905, prohibits the deposit or discharge into navigable streams of any solid refuse or waste. The Act of 1905 provides that the Secretary of War (usually acting through the Chief of Engineers) may issue regulations governing the transportation and dumping into any navigable water or waters tributary thereto of dredgings, earth, garbage, and other refuse material of every kind and description.

(III) Navigation and flood-control

Congress created the Mississippi River Commission by an Act of June 28, 1879, amended by the Acts of March 3, 1881, and July 13, 1892. The law provided that the President and two other members of the Commission should be officers of the Corps of Engineers, United States Army. One member was to be selected from the United States Coast and Geodetic Survey and three from civil life. In addition, the Secretary of the Commission was to be an officer of the Corps of Engineers. The Commission reported directly to the Secretary of War, but has always been under the domination of the Corps of Engineers. By the Act of 1928, referred to subsequently, the Commission was placed directly under the jurisdiction of the Chief of Engineers of the War Department.

Between 1879 and 1928 the Mississippi River Commission was charged with the duty of improving navigation on the Mississippi River, and as an adjunct to such responsibility it naturally undertook to control floods on the lower portion of the River in the interests of navigation. The several Acts relating to the Mississippi River Commission prior to 1928 recognized flood-control, on the one hand, as a National obligation concerned with navigation on the Mississippi and, on the other hand, as a local matter with respect to the protection of adjacent lands from overflow. The several Acts required material contributions from and assumed appreciable construction by both public and private agencies which were interested primarily in the protection of lands from floods. Even as late as 1917, with the passage of the so-called first Flood-Control Act which extended jurisdiction of the Mississippi River Commission to all water-courses connected with the Mississippi River to such extent as might be necessary to exclude flood-waters from the upper limits of any delta-basin, the policy of local cooperation was maintained by a provision that contributions by local interests of substantial percentages of costs of construction was a necessary condition for the use of Federal funds for levee-construction or repair. The amount of this contribution was in each case to be determined by the Commission, but should in no event be less than one-third of the total cost. The Act further required local interests to provide levee rights of way and to maintain the completed levees.

The several Acts relating to both the Mississippi River Commission and the California Debris Commission conferred authority upon the respective Federal agencies to construct levees in the interests of flood-control, but such control was definitely related to the improvement and safeguarding of navigation. Although flood-control from the standpoint of the protection of marginal lands was recognized as a necessary and desirable undertaking, the application of Federal funds thereto was carefully safeguarded by provisions that substantial contributions must be received from local interests, and that such portion of levee or other flood-control works as might be constructed at the expense of the Federal Government should be primarily in the interests of navigation. Over the period of years from 1879 to 1928 the interpretation by Federal agencies of the term "navigation" as applied to works related to flood-control on the Mississippi River and its major tributaries underwent a gradual extension, so that by force of public opinion and otherwise, Federal contributions for flood-control purposes became less and less related solely to the improvement of navigation and were recognized as more and more undertaken for dual purposes of both flood-control and navigation, although depending for their legality upon the latter.

(IV) Navigation and oil-pollution

In 1924 Congress passed the Oil-Pollution Act which prohibits the discharge of oil in or upon the coastal navigable waters of the United States and authorized enforcement by the Secretary of War who operates through the Chief of Engineers. Following the passage of this Act there was an extended investigation of stream-pollution of navigable waters by the Chief of Engineers, and his report recommended against additional Federal legislation concerning water-pollution on inland streams. The Oil-Pollution Act is a good example of one of the series of independent Acts discussed in this paper which bear no relation to one another, nor which have been inaugurated through any concerted National policy. On the contrary, such Acts have been designed to meet particular situations which have arisen from time to time.

(V) Reclamation

For many years the Federal Government had encouraged migration to the so-called "Public Land States," embracing in general much of the area comprising the States and Territories west of the Mississippi River. Much of this area was known to be highly fertile, but agricultural and community life could be maintained only by careful conservation of the limited water-resources and their application to the land by large irrigation-systems. The conservationists of the day, led by President Theodore Roosevelt, secured passage of the Reclamation Act of 1902, which with numerous amendments since that date, has provided for the construction of irrigation-projects in the arid and semiarid States by the Bureau of Reclamation in the Department of the Interior. Such projects are required to be constructed in conformity with State laws. The basic premise of the Reclamation Act has been that costs of the great dams, storage-reservoirs, and irrigation-structures were to be paid for initially by the sale of public lands as authorized by the "Territories Clause" of the Constitution. It was contemplated that the costs would be ultimately returned to the revolving Reclamation Fund by annual payments on the part of settlers in the irrigated regions. While the policy enunciated has remained a fundamental one, it has been departed from in recent years through direct appropriations and by appropriations from Emergency Relief funds which have been applied by the Federal Government to reclamation-projects under special and emergency Acts.

(VI) Federal water-policy up to 1920

The several independent Acts of Congress cited previously constituted until 1920 the chief incursions of the Federal Government into the domain of development, control, or regulation of the water-resources of the country. Until then practically all undertakings of the Federal Government in the water-field, with the exception of reclamation-projects, were strictly related to navigation, and in most instances were bona fide navigation-projects. The principal exception has already been discussed with respect to flood-control along the Mississippi River and to some extent along the Sacramento River. In such instances flood-control came to take on more and more important aspects from both the financial and policy standpoints, but still navigation remained the legal hook upon which was hung practically all river-improvements by the Federal Government.

With respect to the innumerable improvements of rivers and harbors throughout the United States by the Corps of Engineers, acting under the general authority contained in the Commerce Clause of the Constitution, no well-defined National policy has ever obtained. The procedure in general has been for the local interests who were concerned with the improvement of a river or harbor to obtain through their representatives in the Congress authorization directing the Corps of Engineers to make an investigation of the particular project. If this investigation is favorable, it is followed by a more extensive survey and report made to Congress by the Corps of Engineers. Depending somewhat upon the nature of this report, the Congress in general authorizes the improvement to be consummated. A proceeding for review within the Corps of Engineers itself has been set up for such river- and harbor-projects, whereby a given project is reported by the District Engineer to the Division Engineer and then, after review by the Rivers and Harbors Board, is sent to the Chief of Engineers for final recommendations to Congress. At least until 1920 very little if any consideration was given to river- and harbor-improvements as part of any well-defined or even evolving plan for comprehensive development of the nation's water-resources for other than navigation-purposes.

Similarly the great irrigation-developments were generally undertaken as specific projects in areas where irrigation-measures were needed. By and large they were developed solely for irrigation-purposes, and, if power- or flood-control benefits accrued, they were chiefly incidental.

It may be said that at least prior to 1920 the Corps of Engineers, on the one hand, charged with navigation and flood-control projects, and the Bureau of Reclamation, on the other hand, charged with irrigation-projects, pursued their independent ways developing effectively and well the water-resources of the country under specific Acts of Congress charging them to perform specific duties. A comprehensive National water-policy had not begun to evolve.

(VII) Water-Power Act

The Federal Power Act of June 10, 1920, as amended in 1930 and again in 1935, created a Federal Power Commission. This Act had its inception largely because of the difficulties which had arisen in attempts to develop hydroelectric power to meet the growing demands for electric energy consequent upon the industrial development of the country.

Due to the provisions of the Dam Acts, referred to previously, there were navigation-interests to hurdle as represented by jurisdiction of the Corps of Engineers. Moreover, particularly in the West, there were obstacles to be met by possible encroachments on the public lands and the National parks and National forests. Congress had passed Acts in 1896, 1898, and 1901 providing among other things conditions under which power-projects could be developed upon the public lands and reservations. However, the Acts contained little of a policy-nature and their administration was left largely to regulations prescribed by the Executive Departments of the Government.

The legality of the Federal Power Act is chiefly founded upon the powers of the Federal Government over navigation. However, the Act provides that all power-projects constructed on navigable waters of the United States or on tributaries thereto which affect the capacity of these navigable waters, must be approved or licensed by the Federal Power Commission. By extreme interpretation of the term "affecting the navigable capacity of navigable waters" the jurisdiction of the Federal Power Commission might well be practically unlimited.

Furthermore, the Act provides for jurisdiction of the Commission over power-developments at "Government dams," which are defined as "any dam or other work constructed or owned by the United States for Government purposes with or without contribution from others." This phrase has greatly extended the powers of the Commission in recent years due to the large number of dams constructed and to be constructed under the Flood-Control Acts mentioned in the following section. Such tremendous extension of Federal control over water-power could hardly have been envisioned when the Act was passed in 1920.

The Federal Power Act marked the first step toward a National water-policy, by providing that projects approved by the Commission must fit into a comprehensive scheme of river-development. Licenses are issued to public or private agencies, and projects may revert to the United States after 50 years. Accounting and financial practices of licensees must meet with the approval of the Commission. Priority in the issuance of licenses is made to projects to be developed by States and municipalities.

The Federal Power Commission is an independent agency reporting directly to the President and to Congress, and difficulties have already been encountered because certain of its views and interpretation of its powers have failed to coincide with those of various Federal and State agencies which are also concerned with regulatory activities on the streams of the country. Congress has sought by amendments to the Federal power Act to bring all hydroelectric power-projects in the United States into a well-coordinated plan, and little by little appears to be broadening the powers of the Commission so that projects involving hydroelectric power constructed by other Federal agencies, by private interests, and by State agencies must receive the approval of the Power Commission.

(VIII) Flood-Control Acts

Disastrous floods on the Mississippi River in 1927 caused several breaches in the levee-system, and threw grave doubts upon the adequacy of the adopted plans for controlling the floods of that River. As a result, Congress passed the Mississippi River Act on May 15, 1928, which provided for a rather drastically revised plan of flood-control, and definitely asserted that flood-control on the Mississippi River and such of its tributaries as might affect floods on the main stem was a Federal responsibility, although the interests in navigation were mentioned also in the Act. The Mississippi River Commission was reorganized, the President to remain an officer of the Corps of Engineers, but the Commission to report directly to the Chief of Engineers. In essence, of course, this had been a growing practice over the years, and was merely regularized by passage of this Act. The Act undertook to state that Federal interest in flood-control was confined only to the Mississippi River, and did not go beyond that system in its implications with respect to Federal concern in flood-control matters. Furthermore, the principle of local participation in the construction of flood-control works on the Mississippi and its principal tributaries was admitted to be chiefly a Federal responsibility, and the degree of local participation required by previous Acts was greatly reduced.

All of the Acts relating to the control of the Mississippi River and its tributaries from the standpoint of navigation and floods had in essence adopted the Mississippi River Commission's and Army Engineers' long-maintained theory that levees must form the principal flood-control works along the River, although the Act of 1928 provided for outlet structures which were a major departure from previously held theories. By the Overton Act of June 15, 1936, Congress recognized definitely reservoirs as an element in the Federal plans for the control of the floods of the Lower Mississippi River. Thus was ended a long and often bitter argument between the proponents of the previously held theories of the Mississippi River Commission and the ideas of many civilian engineers who were concerned that the Mississippi River and its major tributaries, such as the Ohio, Red, Missouri, etc., should be studied from the larger hydrological elements of whatever methods of flood-control might work best singly or in combination, and with a feeling that some combination of reservoirs, levees, and outlet works would probably prove the ultimate and most economical solution of flood-control on these streams.

By the Omnibus Flood-Control Act of June 22, 1936, Congress for the first time took the bit in its teeth and established a definite Federal policy with respect to flood-control. Section 1 of the Act contains a statement that flood-control of navigable waters or their tributaries is a proper activity of the Federal Government in cooperation with States, their political subdivisions, and localities thereof, and that the investigations and improvements of rivers and other waterways, including watersheds thereof, for flood-control purposes are in the interests of the general welfare, and that the Federal Government should improve or participate in the improvement of navigable waters or their tributaries, including watersheds, for flood-control purposes, if the benefits are in excess of the estimated costs and if the lives and social security of people are otherwise adversely affected. It will appear that this is an extremely broad statement of Federal concern with flood-control, and that Congress has apparently recognized that flood-control in many of its aspects must rest upon enhancement of the general welfare rather than upon improvements to navigation. The Act has not yet been tested in the Supreme Court.

Section 2 of the Flood-Control Act of 1936 provides that Federal investigations and improvements for flood-control and allied purposes shall be under the jurisdiction of, and shall be prosecuted by, the War Department, under the supervision of the Chief of Engineers. It further provides that investigations with respect to watersheds and measures for runoff and water-flow retardation and soil-erosion prevention shall be under the jurisdiction of, and shall be prosecuted by, the Department of Agriculture. Furthermore, it is provided that the foregoing grants of authority shall not interfere with the jurisdiction of the Bureau of Reclamation of the Interior Department pursuant to any general or specific Acts of Congress relating to that Bureau.

Section 3 provided (a provision subsequently removed by the Act of 1938) that no Federal money appropriated by the Act should be expended upon any project until States, political subdivisions thereof, or other responsible local agencies, had given assurance satisfactory to the Secretary of War that all land-easements and rights of way necessary to the construction of the project should be provided without cost to the United States, that the United States should be held free from damages incidental to work of construction, and that such local interests should maintain and operate the works after completion in accordance with regulations prescribed by the Secretary of War. Section 3 also provided further restrictions upon flood-control work to be consummated by the United States dependent upon financial and other participation by local agencies to be benefited.

Section 4 gives the consent of Congress to any two or more States to enter into compacts or agreements in connection with flood-control projects.

Section 5 provides that penstocks or other facilities for future power-development in connection with flood-control structures may be installed in any dam erected under the provisions of the Act, when approved by the Secretary of War upon the recommendation of the Chief of Engineers.

At the time of the passage of the Act, Congress authorized the sum of \$310,000,000 to be appropriated for carrying out a large number of recommended flood-control projects submitted by the Chief of Engineers, together with \$10,000,000 to be appropriated and expended equally by the Departments of War and of Agriculture for carrying out various examinations and surveys provided for in the Act and by other Acts of Congress.

The Flood-Control Act of 1936 had been rather hastily prepared under pressure of certain catastrophes which preceded its passage, and difficulties immediately began to arise with respect to its effective consummation. In the first place, obvious inequities became apparent with respect to flood-control projects in different parts of the country. In regions where flood-

control could best be effected by large reservoirs, local interests were required to pay for the lands and rights of way, which involved very heavy local contributions. In other regions, where flood-control could best be achieved by channel-improvements, or by revetments and flood-walls, local interests were put to a very small proportion of the total cost in supplying easements and rights of way for such structures.

Furthermore, difficulties arose quickly with respect to the compact- and power-provisions of the Act. The New England States achieved a proposed compact which was acceptable to the Chief of Engineers, but when submitted to Congress for ratification, objections were made by the Federal Power Commission because it was alleged that various considerations with respect to power as contemplated in the Federal Power Act had not been taken into account in the compact. As a result, Congress refused to endorse the compact, and the flood-control projects in New England which had been proposed under the compact have remained thus far largely unconstructed, except in instances where relief-funds have been available to supplement contributions by local agencies.

Moreover, some difficulties arose as to the precise jurisdiction between the Corps of Engineers and the Department of Agriculture with respect to investigation of flood-control measures contemplated under Section 2 and Section 9 of the Act.

As the result of the difficulties mentioned above, two amendments to the Act have been passed. The first was the Whittington Amendment of August 28, 1937, which undertook to differentiate between the character of the investigations and surveys to be undertaken by the Corps of Engineers and the several agencies of the Department of Agriculture. The Flood-Control Act of June 28, 1938, removed the major requirements for local cooperation contained in Section 3 of the Act of 1936. This change provides that the United States may itself pay the entire costs of all the lands and rights of way necessary for reservoir-construction. In this way it was hoped to avoid some of the difficulties which had arisen with local authorities, both with respect to the operation of flood-control works by local authorities subsequent to construction, and with respect to controversies which had arisen with local agencies concerning their own power to increase and modify flood-control structures, particularly reservoirs, to provide for multiple-purpose uses in addition to strictly flood-control benefits.

(IX) Soil-erosion control

The Soil Conservation Service was created in the Department of Agriculture by an Act of April 27, 1935. The Act provides for extensive investigations to retard erosion, to improve agricultural practices, and to conserve water. It provides for remedial construction-works under the jurisdiction of the Soil Conservation Service to attain these ends through cooperative agreement with local agencies and individuals. The Soil Conservation Service has expended very large amounts of money in carrying out the provisions of the Act, and to a large extent these undertakings have been concerned with land-practices which are designed to reduce headwater-floods and to conserve soil-moisture. Other agencies of the Department of Agriculture, notably the Forest Service and the Bureau of Agricultural Engineering, have for many years conducted experiments designed to reduce floods and improve stream-regulation as well as to increase infiltration of storm-waters into the ground by various forestry and agricultural practices. The principal motive behind the creation of the National Forests was an intent to protect the headwaters of navigable streams from destructive floods and erosion. It may be said that a large part of the activities of the three agencies of the Department of Agriculture mentioned have been authorized by Congress for the purpose of water-conservation practices, and a National program to this effect may be said to be established. Nevertheless the practices thus far devised have as yet to be correlated with efforts of other Federal agencies concerned with water-regulation and control to become part of any National policy.

(X) Beach-erosion control

A Federal policy of beach-erosion control was enunciated by the River and Harbor Act of 1930, and amended by the Act of June 26, 1936, which authorizes Federal participation in beach-erosion-control investigations up to 75 per cent of the cost. The Acts had their inception in a growing realization of the large damages to property from encroachments by the ocean and other boundary-waters along the seacoasts and the Great Lakes of the United States. With the tremendous increase in the use of these coasts for recreational purposes during the last two decades, a Federal interest in their protection has gradually been growing. Up to the present, Congress has developed only a policy for assistance in the investigation of coastal erosion, and for advice to State and municipal agencies with respect to the design of adequate protective works, except where navigation-projects are affected. The Federal interests in beach-erosion are administered by the United States Beach Erosion Board, consisting of four officers of the Corps of Engineers

and three civilian engineers attached to cooperating State agencies. The Board is under the jurisdiction of the Chief of Engineers of the Army.

(XI) Water-Facilities Acts

By Act of August 28, 1937, Congress adopted the policy of providing facilities for water-storage and utilization in the arid and semiarid areas of the United States. The Department of Agriculture was charged with administration of the Act, which related to small ponds, reservoirs, check-dams, etc. However, by Act of August 28, 1937, Congress appropriated \$500,000 to the Bureau of Reclamation of the Department of the Interior for small storage-reservoirs, any one not to exceed \$50,000 in cost. The regions within the Great Plains were specifically mentioned in the last Act.

(XII) Collection of hydrologic data and hydrologic investigations

For nearly 50 years the Federal Government has pursued a policy of collecting and publishing basic hydrologic data. The Geological Survey of the Department of the Interior, and the Weather Bureau and Bureau of Agricultural Engineering of the Department of Agriculture have been the chief general agencies of the Government for the collection and investigation of data.

Investigations on stream-pollution by the Public Health Service have been carried on under an Act passed by Congress August 14, 1912.

Extensive river-surveys in the interest of navigation, irrigation, flood-control, and power have been carried on by the Corps of Engineers, United States Army, under the Act of January 21, 1927. These are known as the "308 Reports" because authorized by H.D. 308, 69th Congress, 1st Session.

A vast amount of data on the water-resources of the United States is to be found in these reports, many of which have been printed as Congressional Documents dealing with particular rivers. The reports are reviewed from time to time by specific authorization of the Congress.

In 1936, Congress designated the War Department, acting through the Chief of Engineers, as the principal agent to carry out river-investigations for navigation and flood-control purposes, and designated the Department of Agriculture as the principal agency to investigate measures for runoff-retardation and soil-erosion.

(XIII) Special Acts for multiple-use purposes

During the past 12 years, Congress has, under the provisions of a large number of special Acts, provided either directly or indirectly for the construction of an increasing number of extremely large developments of a major character for the conservation and control of considerable portions of several of the major river-basins in the United States. As in the preceding general Acts of Congress referred to previously, these special Acts have had in view usually particular benefits to be conferred in particular regions, and have not formed part of any well-defined National water-policy. However, construction of the projects under these Acts has assisted materially in making the public much more conscious of the importance of large water-projects having in view the production of multiple benefits, as contrasted with projects previously undertaken by the Federal Government directed usually to some single purpose as the chief object. It is not possible within the limits of this article to describe all of the important projects constructed under the authorization of special Acts of Congress during recent years, but a few of the noteworthy are summarized below on account of their great importance in illustrating trends in National policies for stream-management.

Colorado River development--The Colorado River Basin is semiarid to very arid, and includes parts of seven western States and a small area in Mexico. The problem of devising a comprehensive plan for the use of the waters of the Colorado River was long recognized as being of vital importance to the territory drained by it, and as having difficult problems of a national, interstate, and international character. The first step toward the coordinated development of the Colorado River became effective by the passage by Congress in 1928 of the Boulder Canyon Project Act. This Act gave Congressional endorsement to an interstate compact entered into by six of the seven States comprising the Colorado Basin, and provided for the construction of the Boulder Dam and the All-American Canal. The Act also authorized the States involved to enter into various

agreements concerning allocation of the flow of the River. An important part of the Act, making it one of the soundest economic projects thus far constructed by the Federal Government, provided that the cost of the project should be returned to the United States through the sale of hydroelectric power to be generated at Boulder Dam. Lake Mead, the storage-reservoir behind Boulder Dam, has a capacity of over 30,000,000 acre-feet. Portions of this tremendous storage are used for regulation of the River to improve irrigation and domestic water-supplies, for flood-control, for silt-storage, and for hydroelectric power-generation. The regulation of the lower River provided by Boulder Dam has made it possible to undertake other projects, involving the All-American Canal some 300 miles below Boulder Dam, which irrigates vast areas in the Imperial Valley. Also, there has been constructed the Imperial Dam which diverts 15,000 cubic feet per second to the All-American Canal, and there is now under construction the Parker Dam located 150 miles below Boulder Dam, which serves to further regulate the River. The principal purpose of the Parker Dam is to divert water for the Southern California Metropolitan Water-District. This latter project involves the construction of over 200 miles of conduit, which, with the appurtenant pumping and power-works will cost over \$220,000,000. While the Parker Dam and the Southern California Water-Supply undertaking are not specifically authorized in the Boulder Canyon Project Act, they have been constructed in considerable part by Federal funds through provisions of one or another of the Emergency Relief Acts of recent years.

Tennessee Valley development--The Tennessee Valley Authority Act was approved by Congress on May 18, 1933, and amended on August 31, 1935. The objectives were "To improve the navigability and provide for the flood-control of the Tennessee River; to provide for reforestation and the proper use of marginal lands in the Tennessee Valley; to provide for the agricultural and industrial development of said Valley; to provide for the national defense, ..." This Act provides for the most extensive comprehensive development of a river-system by the Federal Government that has yet been undertaken in this country. The Tennessee Valley Authority is administered by a board of three directors appointed by the President subject to confirmation by the Senate. The initiation of large-scale developments on the Tennessee River began with the construction of Wilson Dam by the Corps of Engineers of the War Department. This was authorized by Congress in the interest of national defense, and was completed in 1925. Subsequently the Tennessee Valley Authority will have completed four additional dams, and has three more dams under construction or authorized for construction. The Act is definitely related to the navigation-powers of the Federal Government by the provision that one of the principal purposes is to provide nine-foot navigation from Knoxville, Tennessee, to the mouth of the Tennessee River. The Supreme Court, in a recent decision affecting the Tennessee Valley Authority, rested its decision upon the elements of navigation of the Act, and the other purposes of the Act have never yet been tested as to their constitutionality.

The operation of the dams is directed by law to be in the interests of navigation and flood-control, and in addition the Authority is authorized "so far as may be consistent with such purposes" to generate and sell power to assist in liquidating the cost or aid in the maintenance of the projects of the Authority. The power-projects are to be made self-supporting through the sale of power as soon as possible. Preference in sale of power is to be given to public agencies, and competition with private utilities is designed to provide a "yardstick" by which to measure fairness of the rates of the latter. In addition, consideration is to be given to the development of fertilizer, the proper use of marginal lands, reforestation, and the general economic and social well-being of the people living in the river-basin. With these broad powers, the Tennessee Valley Authority has undertaken a comprehensive development of the River and its major tributaries, the estimated costs of the dams alone being in the neighborhood of \$335,000,000. Marked benefits from flood-regulation have already been secured, and a very large amount of power is being generated. As an experiment in over-all development of a large drainage-basin of the United States by Federal authority and under a Federal agency, resting the power for such wide-spread activities chiefly upon the "Commerce Clause" of the Constitution, the completion of the planned projects of the Tennessee Valley Authority will be one of the most significant indices of the effectiveness and desirability of Federal participation in river-management which has ever been undertaken in any country.

Other large projects--The Federal Government, under authority of Emergency-Relief Acts or the Flood-Control Acts, is participating largely in the construction of a number of extremely significant multiple-purpose river-developments in various parts of the country other than those enumerated in detail above. The Central Valley Project in California envisions the construction of large dams for regulating the flow of the Sacramento and San Joaquin rivers, for the improvement of irrigation, the development of power, the reduction of salinity in the lower portions of the rivers, and for flood-control. The Columbia River developments were initiated by the construction by the Corps of Engineers of the Bonneville Dam and power-project in 1933. Subsequently, Congress passed the Bonneville Act on August 20, 1937. This provided for the completion of the project, and involved multiple-purpose use for navigation and power-development pri-

marily. More recently the Bureau of Reclamation has been authorized to proceed with the construction of the Grand Coulee Dam on the upper portion of the Columbia River, which will have an important effect in regulating the River, but which is primarily designed for the development of irrigation and hydroelectric power. These two projects of great magnitude formed the initial steps in the comprehensive plan for the entire development of the Columbia River. Another and somewhat different undertaking which has been consummated is the Muskingum Flood-Control Project, which was constructed by the United States Engineer Corps on behalf of the Muskingum Watershed Conservancy District, a State authority. Of the cost of the Project, which is designed primarily for flood-control through the development of 14 reservoirs, the cost was divided as follows: \$22,590,000 from Federal Emergency Relief funds; \$8,000,000 from the Muskingum Watershed Conservancy District; and \$4,000,000 directly by the State of Ohio. The Muskingum Flood-Control Project can hardly be called a multiple-purpose project, but is an example of a well-coordinated scheme for flood-control purposes on a fair-sized drainage-area and constructed by a rather unusual combination of State and Federal funds. It is significant that a recent Flood-Control Act provides that the State's contribution shall be reimbursed by the Federal Government, now that the provisions of the Flood-Control Acts of 1936 and 1938 are in effect.

Summary

It appears from this review that prior to 1920 Federal policy with respect to water was fairly definitely restricted to navigation and irrigation. Since then new Acts have created new agencies and new powers for old agencies which have immeasurably increased the responsibilities of the Federal Government. Nearly all of the newer enactments have been aimed at some specific objective and usually have originated as a result of some large-scale calamity such as the floods of 1927, 1936, and 1937, the drought of 1934-35, the agricultural difficulties in the Great Plains from 1934 to 1936, etc.

Provisions for adequate investigation prior to construction and for sound economic justification of projects have been conspicuously absent both in many of the Acts cited and in the policies followed for their initiation and development. While this review confines itself to specific Acts of Congress directly affecting water-policy or water-projects involved therein, it should be noted that some 34 different Federal agencies, including those mentioned herein, have some fairly direct relation to water-problems. These agencies have established policies and practices which are often difficult to reconcile, and have engaged upon water undertakings unknown to each other and sometimes in conflict. Serious attempts to solve these different problems are being pursued by most of the Federal agencies concerned, particularly through their participation in the activities of the Water Resources Committee, described subsequently.

The specific and generally uncoordinated Acts from 1920 to 1938 represent material progress toward a National water-policy. They were not designed, however, toward this end, and it has not yet been possible to utilize them effectively as interlocking parts of a planned Federal program for the conservation, use, and control of water- and land-resources. Some of the disadvantages of this were apparent as early as 1933 when the emergency-relief agencies were created. Subsequent new special agencies with special directives have still further accentuated the need for over-all planning and coordination, and the more effective development of an integrated National water-policy.

An approach to coordination

Recognition of these difficulties has led to the initiation of deliberate efforts to coordinate the activities of various Federal Agencies, to develop cooperation with State and local agencies, and to gradually evolve an adequate National water-policy.

Beginning with the President's Committee on Water-Flow appointed in the winter of 1934, and consisting of the Secretaries of Interior, War, Agriculture, and Labor, the work (on coordinated stream-management) has gone through several stages with different emphases or purpose. The first report brought together through the offices of the National Planning Board was a kind of compendium of water-projects drawn from the '308' reports of the Army Engineers and the experience of the Bureau of Reclamation.

Concurrently, the Mississippi Valley Committee of the Public Works Administration was at work on water-problems of the two-thirds of the country drained by the 'Father of Waters.' Its report, transmitted to Congress on January 24, 1935, brought new recognition of the broad problems of social and economic policy inherent in water-planning. Through the dramatic and colorful manner in which the material was presented, the administration and the public were interested in multiple-purpose projects for water-use. [Progress-Report, National Resources Committee, October 1937.]

The National Resources Committee (successor to the National Planning Board, 1933, and the National Resources Board, 1934) was constituted by Executive Order of June 7, 1935. Among other duties, it was to use its good offices to promote programs for the development and use of land, water, and other National resources. The Committee consists of eight members, of whom six are high administrative officials of the Government and two are experts from outside the Government.

service. The Water Resources Committee (which is the agent of the National Resources Committee in matters relating to water) is composed of 12 members, eight of whom are executives of major Federal Departments dealing with water, two are engineers connected with State engineering agencies, and two are non-Government experts in different fields of water-use and control. Both in the National Resources Committee and the Water Resources Committee, there is represented the specialized knowledge and attitudes of Federal and State agencies, with the leaven of outside business men and professional experts. The union of these forces and the merging of their respective views and wisdom have proved an unexpectedly satisfactory approach to cooperative and coordinated effort.

The Water Resources Committee has developed its procedures gradually during the past four years, and has at present the following principal types of undertakings in operation:

(1) The elucidation of primary water-problems, the evaluation and listing of desirable water-projects, and the development of programs and plans for comprehensive water-resources use and control in each principal drainage-basin of the country. This has been the major single undertaking of the Committee during the past three years. A preliminary report was issued in 1936, and a second and more conclusive report was issued in 1938.

(2) The coordination of water-activities of Federal and State agencies. This it has accomplished in a variety of ways. For example, (a) it has established a procedure for clearing-house review of future flood and flood-control investigations by Federal agencies to provide proper consideration of related problems of water- and land-use, and (b) it has also established a mechanism for reconciling conflicts over and reducing unwise action with respect to land-drainage and water-storage activities of the Federal Government.

(3) The establishment of coordinated programs for the collection and publication of basic hydrologic data, including projects of investigation and research. A report on "Deficiencies in hydrologic data" has been printed, with a program for remedying the principal defects. A report on "Deficiencies in hydrologic research" is now in press.

(4) Participation with State or regional groups in special drainage-basin investigations. Elaborate and comprehensive reports on the Red River of the North and on the Upper Rio Grande have been published. Different procedures have been developed in different areas, and out of these varying approaches there may be expected in the course of time improved methods acceptable and applicable to specific problems and regions.

(5) Special investigations involving more than one Federal or State agency. Examples are the reports on a National policy for the control of water-pollution and on the design of low dams, and reports in progress on effect of vegetal cover on water-control, the economic appraisal of flood-damage, etc.

As various specific undertakings have been initiated, the fixed policy of the Committee has been as follows:

(a) To confine its activities solely to coordination and investigation, and to reject any undertakings of an executive, administrative, or construction nature.

(b) To utilize regional and State planning organizations in every possible way.

(c) To utilize the services of expert water-consultants and other technicians for specific undertakings. Such experts are usually assigned to work with regional or local agencies.

(d) To be guided in the preparation of reports by the views of representatives of Federal bureaus and by the investigations carried out under the procedures described in items (b) and (c) above.

Characteristics of a National water-resources policy

The reports on drainage-basin problems and programs, as well as the other undertakings of the Water Resources Committee, have in general been guided by the following characteristics which the Committee feels should be the basis of any sound water-policy ["Drainage-basin problems and programs," National Resources Committee, December 1936]:

"(1) It will be concerned, in the final analysis, not with water per se, but with the promotion of public safety, public health, the public convenience and comfort, the economic welfare of the public, the establishment or maintenance of a high standard of living.

"(2) It will seek to promote the maximum integrated use and control of water, within the shifting limits imposed by considerations of technical feasibility and of economic and social justification.

"(3) It normally will treat drainage-areas as units with respect to their waters in recognition of the train of connected problems that runs from river-source to river-mouth.

"(4) Though treating the drainage-areas as units, it will scrupulously observe the rights of the several States both in intrastate and interstate streams, seeking through cooperation to promote the full use of water in the best ways and in the proper places.

"(5) It will recognize and abide by the axioms that facts are indispensable prerequisites to sound action with respect to water, and that conclusions and commitments not based on predetermined facts almost certainly prove indefensible. In keeping with this recognition, it will promote by all feasible means continuous assembly of the basic data essential for an evolving unending water-plan. At the risk of repetition, the statement may be made categorically that the adoption of a plan and program for the use and control of the waters of any river-basin without a definitive study of adequate data bearing on all phases of the interlocking physical and cultural problems involved would be illogical, would result in economic waste, would invite controversy, and might preclude desirable action later. As already noted, controversies over water multiply. They are most likely to arise where pertinent facts are least known. An enlightened water-policy will seek to obviate controversy by substituting facts for opinion.

"(6) It will assign the cost of constructing and operating projects undertaken from time to time as suitable elements in an evolving water-plan among the agencies concerned in as close accordance as possible with the distribution of benefits. The proposition that those who will profit from a given undertaking normally should pay, in a manner not involving avoidable or undue hardship, in proportion to the advantage they will reap, should be the basic principle of action.

"(7) In determining whether or not water-projects are justifiable, and in distributing the costs of meritorious projects among the beneficiaries, it will take properly into account social benefits as well as economic benefits, general benefits as well as special benefits, wherever they are involved. Some of these benefits are not capable of measurement, and accordingly they commonly have been ignored in the past in evaluating certain types of enterprises. They are subject to reasonable appraisal, however, and their intangible nature will not justify their neglect in the future. In great measure, they concern the public at large. A public water-policy should assiduously conserve and promote public interests. To this end, social accounting must take its place with economic accounting. As effective water-planning proceeds year after year without interruption--planning based on fundamental and exhaustive engineering, economic, and social studies that cover all relevant conditions--there inevitably will result not only a clearer understanding of what constitutes the public interest, but also a greater opportunity to promote it through equitable control and orderly development of water-resources."

Practically all of this paper relates to water. Yet it becomes increasingly evident that we cannot, as a nation, and that we should not, as enlightened engineers, consider a program for water-use and control as merely an aggregation of hydraulic and sanitary engineering projects. A comprehensive river-survey involving the most effective use of the stream for producing power or improving navigation, or both, involves only certain elements, and perhaps minor elements in a water-policy for the basin. Sound economic appraisal of real flood-control costs and benefits, public water-supply, increase of low-water flow from storage to abate pollution, the necessity for water-recreation, the balance between cost of sewage-treatment and increased storage for low-water control, the relation of land-practices to silting of reservoirs, and the economics of soil-erosion control and forestation as affecting both land-use and water-use, are only a few of the interrelated factors to be considered.

It takes time, ability, and vision to solve effectively the complex water-land equation for a given drainage-basin or region. No National water-plan is feasible, but a well-considered National water-policy is in the making. By knowledge, cooperation, and informed public opinion, there is being worked out a realistic approach toward adequate stream-management in the United States. Proceeding on various fronts, set back from time to time, by political expediency, bureaucratic jealousies, or lack of knowledge; recast as new information or new needs or changed public opinion develop, methods and procedures acceptable to this country are slowly evolving a policy which is designed to conserve, develop, and control the vast water-resources of the nation for the use and convenience of its citizens.

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FLOOD-DATA IN THE UNITED STATES

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Flood-data is the designation herein applied to information concerning floods, statistical as well as analytical, needed by engineers and public officials in the formulation of plans for protection against high water and in the construction of structures such as dams, bridges, and storm-drainage channels. The statistical phase is concerned with the cataloging and publishing of factual data derived from observations on rainfall, runoff-rates, flood-stages, and discharges. The analytical phase is aimed at determining from the observed data the frequency of occurrence and geographical distribution of flood runoff-rates.

On account of the large territory embraced by the United States, the relatively brief occupancy of the country by whites, and the relatively low population-density in most of its parts, the history of the collection and analysis of flood-data in the United States takes on a distinctly different aspect from that found in the older countries where flood-problems and records extend over several centuries. There, important flood-events have been observed over long periods--on some rivers for more than 1000 years--while in the United States the great floods of the past, for which reliable figures are available, cover but scant 250 years, and a century-record of flood-heights is classed as long.

The number of day-by-day stage and discharge-records on American rivers which cover half a century and longer totals well over 100. River-stage records in many instances cover from 80 to 100 years and longer. Thus, the first observations on river-height at St. Louis were made in 1785, although regular daily observations did not begin until 1861. Early gage-readings were made at Vicksburg in 1828 and regular observations were begun in 1871. Cincinnati and Pittsburgh gages have been read continuously since 1858. About 1879 the Signal Service of the United States Army began making regular observations at a number of gages which later were taken over by the United States Weather Bureau.

The use of the current-meter for stream-flow measurements began about 1882 simultaneously on navigable rivers and on the small streams of the western irrigated areas. Previously, measurements of the flow of water in natural streams had been undertaken by means of crude devices; and the division of water among different users for placer mining and irrigation was made by means of orifices, the unit of measurement being the Miner's Inch. On large rivers rod-floats were used for many years. On the Mississippi and Ohio rivers discharge-measurements by means of floats were made as early as 1851. The first current-meter measurements made in the United States on large rivers were undertaken under the direction of the Mississippi River Commission in 1882. The equipment included a current-meter designed by General Ellis and another designed by Clemens Herschel. The Ellis meter had revolving cups mounted on a vertical shaft and the Herschel meter was of the horizontal-shaft propeller-type. An improved cup-meter designed by W. G. Price was developed in 1882 and was used in measuring the discharge of the great flood of that year in the Ohio River. In 1888 in connection with Interior Department surveys relating to irrigation, ordered by Act of Congress of October 2 of that year, current-meter measurements were started on the Rio Grande at Embudo, New Mexico, on December 21 using a modified Herschel meter. Systematic stream-gaging throughout the United States did not get its start, however, until 1895 when the Hydrographic Division (now Water-Resources Branch) of the United States Geological Survey was created for the purpose of "gaging streams and determining the water-supply of the United States and for the preparation of reports upon the best methods of utilizing the water-resources." Although none of the work so undertaken had specific reference to floods, except as flood-waters might be valuable through storage for irrigation or other uses, the completeness and continuity of the resulting records proved to be of great value in the recording of flood-stages and discharges and in establishing the frequency of occurrence of floods of all sizes on both navigable and non-navigable streams. On March 1, 1917, Congress passed what has since become known as the "first flood-control act." It provided funds for enlarging the inadequate levee-systems on the Sacramento and Mississippi rivers, but did not expressly recognize flood-control to be a Federal function. In the meantime, many serious flood-problems had arisen as towns, cities, and industrial plants continued to crowd in on the flood-plains of rivers.

The history of the collection of flood-data in the United States is linked intimately with the successive steps in the utilization of the country's water-resources incident to settlement and the progressive requirements of man. Gages were first established for noting the rise and fall of river-stages for the use of inland navigation. They were followed by additional river-gages as disastrous floods became matters of public concern and the desire for flood-forecasts became insistent. In 1879 Congress created the Mississippi River Commission for the improvement of the Mississippi, at first to improve navigation, and later to curb floods. Under its direc-

tion a large amount of information relating to flood-stages and discharges has been obtained and published.

One of the important milestones in the history of American flood-data is the report of the Pittsburgh Flood Commission in 1911. The great flood of 1913 in the Ohio Valley and the destruction wrought at Dayton and neighboring towns in the Miami Valley brought about the creation of the Miami Conservancy District in 1915 and the framing of the Conservancy Act of Ohio, the first comprehensive flood-control legislation written in the United States. In 1917 there were published by the Miami Conservancy District the Technical Reports on "Great storms in eastern United States" and "Hydraulics of the Miami Conservancy District."

Among other events that have created interest in floods and in flood-data were the great floods of 1902 and 1903 in the Passaic River in New Jersey and the great floods of 1903 and 1904 at Kansas City.

About 1903 the United States Geological Survey began publishing data concerning "destructive floods." Water-Supply Papers Nos. 88 and 92 described the Passaic River floods of 1902 and 1903, and Water-Supply Papers Nos. 96, 147, and 162 described the floods of 1903, 1904, and 1905 in various parts of the United States.

In 1902 the United States Weather Bureau was created. Flood-forecasting and the publication of flood-events and flood-damages were undertaken by this Bureau, and in the course of time it built up the most complete month-by-month information on flood-heights and damages in all parts of the United States. This Bureau has published daily river-stages for many points on the large rivers since 1892. Flood-data are published monthly in the Monthly Weather Review, and special reports are issued for the greater floods as they occur. Among these, Bulletin M on "Floods of the spring of 1903," Bulletin Y on "Floods of 1912, Mississippi and Ohio rivers," and Bulletin Z on "Floods of 1913" are conspicuous in the early literature on flood-data in the United States; for the more recent floods, see Supplement No. 37, Ohio and Mississippi flood of January to February, 1937.

In 1913 the State of Pennsylvania undertook a comprehensive inventory of its water-resources, which included the first detailed inventory of floods made by any State. This inventory was published in 1917 as Part VIII of the Water-Resources Inventory, entitled "Floods," and contained lists of the great historic floods of which record could be found, among them the flood of February 27, 1892, which wiped out the first settlement at Trenton, New Jersey, on the Delaware River, and the great floods of 1762 and 1763 on the Ohio River at Pittsburgh, Pennsylvania.

The period of 1905-15 is notable for the advent of flood-water conservation by means of high-dam storage-reservoirs for use in irrigation and hydroelectric projects. This provided a marked stimulus for securing additional stream-flow observations.

Of recent years the National Resources movement and flood-control legislation have been instrumental in promoting interest in stream-flow data, including flood-data, with the result that stage-observations accompanied by frequent discharge-measurements are now being made at more than 3500 regular gaging stations in the United States.

In 1922 the American Society of Civil Engineers appointed a committee from its membership on "Flood-Protection Data" for the purpose of stimulating interest in the collection and publication of information pertaining to floods. In 1934 this Committee assisted the United States Geological Survey in the preparation of the first comprehensive publication of flood-data, financed by funds allotted by the Public Works Administration. The resulting report, entitled "Floods in the United States--magnitude and frequency," was issued in 1936 as United States Geological Survey Water-Supply Paper No. 771. This report has been followed by several Geological Survey reports treating of specific floods, notably Water-Supply Papers Nos. 798, 799, and 800 on the "Floods of March 1936," and No. 838 on the "Floods of the Ohio and Mississippi rivers, January-February 1937."

By direction of Congress, studies were undertaken by the Engineer Corps of the United States Army on the possibilities of comprehensive development of streams with respect to navigation, flood-control, and power-development on more than 200 rivers in the United States, commencing about 1928. Some of these studies are still in progress. The many flood-control projects which have been ordered undertaken by Congress as the result of these studies have been instrumental in promoting detailed analysis of flood-data and of the frequency of occurrence of floods of various magnitudes. These studies have brought to light the immensity of the annual flood-damage in the United States, which tends to increase from year to year because of the more intensive occupancy of the valleys.

Efforts are now being made through meteorological research to determine the maximum storm-rainfall that is possible of occurrence in any given watershed, in order to ascertain what are likely to be the maximum rates of flood-runoff to be expected. This work is being conducted by the Hydro-Meteorological Section of the River and Flood Division of the United States Weather Bureau in cooperation with the Corps of Engineers of the United States Army. The immediate present needs are for more and better field-observations, especially of automatic records of both precipitation and river-stages, and for means for communicating such information with the least possible delay to flood-forecasters and engineers who operate flood-control works.

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GREAT FLOODS IN THE UNITED STATES

C. S. Jarvis

From fragmentary historical notes and native legends, we are accorded a somewhat hazy view of flood-phenomena under primitive conditions and are led to the conclusion that those phenomena occasionally assumed proportions approaching more or less closely to those observed during the later record period. Reasoning from cause to effect and consideration of specific examples in many localities, support the opinion that frequencies as well as magnitudes have increased, resulting either directly or indirectly from man's occupation and disturbance of the drainage-areas, the vegetal cover, the flood-plains, and facilities for surface-detention.

Apparently the sampling method may most satisfactorily serve to afford a summarized account and comprehensive view of notable floods in the various regions and wide range of river-systems represented in this country. Indeed, were it not for such devices as graphic charts, maps, and tabulations, it might require volumes to attain the objective.

New England floods--New England floods have had historical and economic significance over a long period due to the early colonization and industrial developments, involving the use of water-power and thus exposing valuable plants, machinery, materials, and products within the reach of destructive flood-stages. Despite the lessons learned with each succeeding catastrophe, it was reserved for the floods of March 1936 to cause the worst damage and destruction experienced during the 300 years following white settlement. Strange as it may appear, the actual precipitation during the worst storm of the series had been exceeded by at least seven storms listed and analyzed in connection with the Miami Conservancy District [Technical Report, Part 5, revised, Dayton, Ohio, 1936]. These seven outstanding storms had occurred during October 3-4, 1869, May 31-June 1, 1889, May 19-21, 1894, July 12-14, 1897, November 3-4, 1927, March 24-25, 1913, and August 23-24, 1933. There can be no reasonable doubt that others of like character had occurred during the preceding two centuries of sparse and intermittent records. Probably the water-content of snow on the ground in early March 1936, ranging generally from five to 10 inches and representing most of the winter's accumulation, accounts for the unusual severity of floods throughout the New England river-systems and the notable rise in the Connecticut River at Hartford to a stage 8.6 feet higher than previously recorded during 300 years.

Detailed studies of hydrologic data in connection with outstanding floods in New England disclose many instances of such phenomena as intense and sustained rainfall on accumulations of snow and ice; but never before had it been demonstrated that the congealed moisture awaiting such sudden release could effectually double the maximum observed daily precipitation. Such occurrences seem to demand more liberal provision for both channel- and reservoir-capacities than have been ordinarily deemed advisable in this region, in order to provide against the worst combination of physical and meteorological conditions. With rainfall and water-content of accumulations of snow almost equally divided and totaling as high as 20 inches over large areas, a runoff-factor of 70 to 90 per cent accounts for the unprecedented flood-peaks and the total volumes discharged as of March 9-22, 1936.

Middle Atlantic States floods--The New York State flood of July 1935 established new records for both rainfall-intensity and amount as illustrated in Table 1 [from United States Geological Survey Water-Supply Paper 773-E, p. 237]; some of them representing an excess of more than 50 per cent over previous precipitation-records. Because of its wide-spread damage, estimated at \$25,000,000, the hundreds of residents rendered homeless, the 43 deaths among inhabitants, and the devastation visited upon a farm-belt 200 miles long from Hornell and Ithaca to the Catskill Mountains, and 50 to 75 miles in width from the Pennsylvania boundary to the Mohawk Valley, this flood has taken rank as the most tragic occurrence recorded within that immediate region. Always

Table 1--Comparison of greatest recorded precipitation, in inches, for 24-, 48-, and 72-hour periods, at stations in south-central New York
(Prepared by United States Weather Bureau, Ithaca, New York)

Station	Length of record (years)	24-hour		48-hour		72-hour	
		1935	Previous	1935	Previous	1935	Previous
Ithaca	77	7.90	4.70	9.25	5.88	9.50	5.96
Cortland	57	7.67	5.80	10.58	6.47	11.15	7.82
Norwich	29	6.10	4.04	9.07	4.94	9.56	5.25
Delhi	22	8.52	5.71	8.68	6.44	9.43	6.49
Haskinsville	36	3.35	2.80	6.70	3.61	6.76	4.25
Oneonta	41	5.24	5.09	6.71	5.18	6.94	5.26
Burdett	3	8.50	....	10.50	....	11.10	....
Ovid	3	7.61	....	9.84	....	10.61	....
Hammondsport	3	6.10	....	8.00	....	8.47	....

therefore, throughout the period of record, the glaciated surface, permeable soils, and abundant facilities for storage or detention had been more or less commensurate with the rainfall.

The general storm and attendant floods of May to June, 1889, extending over large areas on both the east and west slopes of the Appalachian Mountain System from Virginia to New York, reached its climax in west-central Pennsylvania, not primarily because of the recorded eight-inch daily maximum intensity of the storm, although that was notable, but rather because of the sudden failure of an earth-dam which was overtopped throughout its length, thus releasing some 10,000 acre-feet of stored water into the swollen stream in a narrowly confined valley above the prosperous industrial city of Johnstown on the Conemaugh River, resulting in a toll of more than 2200 human lives. This same storm brought the Potomac River stage up to 36.0 feet at Harpers Ferry; later exceeded by 0.6 foot on March 19, 1936. However, the resulting flood-crest at Washington, D. C., in March 1936 was nearly equaled June 2, 1889, and has not been closely approached by any other flood of record on the Potomac.

Southeastern States floods--Proximity to the South Atlantic, the Gulf of Mexico, and the West Indies, all associated with the genesis of major storm-disturbances in this part of the globe, readily accounts for (1) the greater number of southern storms qualifying for detailed study and plotting by the Miami Conservancy District--209 as compared with the 71 northern storms within the 42-year period, 1892-1933, above noted, and (2) the greater daily maximum and total precipitation-depths attained. Were it not for the compensatory influence of mild climate, relatively immune to such hazards as snow- and ice-accumulations, frozen ground, entirely dormant and defoliated vegetation, and bare ground, the flood-phenomena of the Southeastern States should normally attain magnitudes about proportional to rainfall-intensities and amounts, approximately double those observed in the Northeastern States. However, they are fairly comparable in flood-flow from equal areas.

As would be normally expected, about one-seventh or 31 of the 209 storms listed in Part V of "Technical Reports, Miami Conservancy District," were centered in Florida, due to the exposed position. There the gentle surface-gradients, the open granular character and high infiltration-capacity of prevailing soil-types, and the vegetative cover accomplish much in the reduction and regulation of flood-flows. Low velocities, moderate peaks, wide-spread lateral inundation, and immense valley-storage characterize many of the Florida rivers.

In contrast with the coastal plains rivers, those flowing from the mountainous regions of the Carolinas, Tennessee, Georgia, and Alabama, with meager valley-storage and relatively steep gradients, are capable of attaining high velocities and correspondingly great erosive power, with devastating effects along their course. The upward deflection of tropical air-masses along their course inland, due to orographic obstructions, seems to produce precipitation-intensities and amounts nearly comparable with those observed along the South Atlantic and Gulf coasts. At least two or three flood-producing storms of State-wide proportions may reasonably be expected within the Southeastern States every year, according to past experience, in one or more States.

Ohio River System floods--The Ohio River Basin, comprising 203,000 square miles, or about one-seventh of the Mississippi Basin, has proved its ability to deliver one-half or more than two-thirds of the maximum recorded peak-discharge of the Mississippi in April 1936 and February 1937, respectively. The conditions accounting for such high flood-potentialities as have been manifested, even after the completion of notable storage or detention and regulating projects on various tributaries, are the generally copious rainfall during average years, the possible

tendency for storms to follow and occasionally to hover in the valley-troughs, and the compact, oval-shaped form of basin. Such combinations of factors contributing to synchronism of flood-crests may be observed not only at various stations along the Ohio, from Evansville to Pittsburgh, but also on several of the larger tributaries, such as the Wabash, White, Muskingum, Kentucky, Kanawha, Monongahela, and Allegheny.

Fortunately for the record, grave concern of military leaders as to the safety of their powder-magazines against flooding, at old Fort Duquesne at the apex of the triangle in Pittsburgh,



FIG. 1—MAXIMUM FLOOD-FLOWS

Table 2--Flood-stages of Ohio River at Pittsburgh, Pa. (base gage-height 20.7 feet)

Date	Gage-height feet	Date	Gage-height feet	Date	Gage-height feet
1762 Jan. 9 P	39.2	1873 Dec. 14 P	28.9	1889 June 1 P	27.2
1763 Mar. 9 P	41.2	1874 Jan. 8	25.4	June 2	25.0
1784	38.2	Jan. 8 P	25.8	1890 Jan. 17	20.8
1787 Jan. P	35.2	Dec. 30	23.2	Jan. 17 P	23.2
1806 Apr. 10 P	37.1	Dec. 30 P	24.2	Feb. 21	21.5
1807 May 18 P	30.1	1875 Mar. 16	23.7	Mar. 23 P	27.5
1810 Nov. 11 P	40.2	Apr. 3	21.2	Mar. 24	25.7
1813 Jan. P	32.2	Aug. 3	24.2	Apr. 10	21.8
1816 Feb. P	36.2	Aug. 3 P	25.1	Apr. 10 P	22.0
1832 Feb. 10 P	38.2	Dec. 28	23.5	May 25	22.7
1840 Feb. 1 P	30.0	Dec. 28 P	24.8	May 25 P	25.2
1846 Mar. 15 P	28.2	1876 Feb. 12	20.7	1891 Jan. 3	26.2
Dec. 20	23.2	Sep. 19	24.0	Jan. 3 P	26.4
1847 Feb. 2	30.1	Sep. 19 P	28.2	Feb. 3	21.0
Nov. 25	26.2	1877 Jan. 17	25.3	Feb. 11 P	22.9
Dec. 12	27.2	Jan. 17 P	27.8	Feb. 18 P	34.5
Dec. 18	21.2	Nov. 25	21.4	1892 Jan. 15	26.1
1848 Dec. 22	26.2	1878 Nov. 28	21.9	Jan. 15 P	26.2
1850 Dec. 8	23.2	Dec. 11	26.6	1893 Feb. 8	26.3
1851 Sep. 20	34.1	Dec. 11 P	27.7	Feb. 8 P	27.2
1852 Apr. 16	30.2	1879 Jan. 29	23.0	Feb. 11 P	25.2
Apr. 19	35.1	Mar. 12	23.1	Apr. 22	21.3
1855 Mar. 18	21.2	1880 Feb. 14	24.8	May 18	23.0
Apr. 14-15	22.7	Dec. 6	21.7	1894 May 22	25.7
1856 Apr. 18	21.7	1881 Feb. 11	26.4	May 22 P	26.4
1857 May 6	24.5	Apr. 14	21.7	1895 Jan. 8	28.9
Dec. 11	21.2	June 10	28.3	Jan. 8 P	29.0
1858 May 27 P	29.2	June 10 P	30.3	Apr. 11	23.4
Dec. 16 P	23.2	1882 Jan. 14	21.2	1896 Mar. 31	23.8
1859 Feb. 20	23.2	Jan. 28	24.7	July 26	25.0
Apr. 23	22.4	Feb. 22	24.3	July 26 P	26.2
Apr. 27-28	25.2	Mar. 22	21.5	1897 Feb. 24	32.1
1860 Jan. 15	21.2	1883 Feb. 5	28.0	Feb. 24 P	32.7
Apr. 12 P	32.9	Feb. 8	30.0	Mar. 7	21.9
Nov. 4	25.2	Feb. 8 P	31.2	1898 Jan. 17	21.0
1861 Sep. 29	34.2	Feb. 12	23.8	Jan. 24	22.9
Nov. 4	21.2	Feb. 16	23.9	Mar. 24	31.7
1862 Jan. 21	33.2	Dec. 25	22.0	Mar. 24 P	32.1
Apr. 9	22.7	1884 Feb. 1	23.6	Mar. 31	20.7
Apr. 22	29.6	Feb. 6	35.1	1899 Mar. 6	24.3
1863 Dec. 16	21.6	Feb. 6 P	36.5	Mar. 6 P	25.2
1864 Apr. 11	21.2	Feb. 12	21.5	Mar. 30	22.4
Dec. 18	22.7	Feb. 15	24.0	1900 Jan. 22	21.0
Dec. 20	22.7	Mar. 13	22.1	Nov. 27	30.5
1865 Mar. 4 P	27.7	1885 Jan. 17	25.2	Nov. 27 P	30.9
Mar. 19 P	34.6	Jan. 17 P	26.2	1901 Mar. 12	22.6
Apr. 1	22.2	1886 Jan. 6	23.4	Mar. 12 P	23.0
May 13 P	24.8	Feb. 14	22.7	Mar. 28	20.7
Dec. 23	21.2	Apr. 1	23.2	Apr. 7 P	25.3
1866 Feb. 14	20.7	Apr. 7	25.4	Apr. 8	24.2
1867 Feb. 15-16 P	25.2	Apr. 7 P	25.8	Apr. 21	30.6
Mar. 13	26.7	1887 Feb. 4	23.2	Apr. 21 P	30.7
1868 Mar. 18 P	25.2	Feb. 9	22.2	Dec. 16 P	29.0
Sep. 26	21.2	Feb. 12	25.1	1902 Mar. 1 P	35.6
1869 Mar. 31	22.7	Feb. 12 P	25.2	Mar. 2	33.5
1870 Jan. 19	21.2	Feb. 27	23.5	Apr. 10 P	23.8
1871 Jan. 17	21.7	Feb. 27 P	25.2	Dec. 14	20.7
1872 Apr. 11	23.2	1888 Jan. 8	24.5	1903 Jan. 31	24.0
Apr. 11 P	23.8	July 11	24.5	Jan. 31 P	24.2
1873 Jan. 6	23.4	July 11 P	25.2	Feb. 5	26.7
May 4	21.7	Aug. 22	26.2	Feb. 5 P	27.2
Dec. 14	27.7	Aug. 22 P	29.2	Feb. 17	24.5

Table 2--Concluded

Date	Gage-height	Date	Gage-height	Date	Gage-height
	feet		feet		feet
1903 Feb. 17 P	25.1	1912 July 26	22.2	1924 Oct. 1 P	23.6
Mar. 1	30.7	July 26 P	22.9	1925 Feb. 12	23.9
Mar. 1 P	32.1	1913 Jan. 9 P	34.5	Feb. 13 P	25.1
Mar. 10	23.2	Jan. 12 P	29.5	1926 Feb. 26 P	22.3
Mar. 10 P	23.3	Jan. 13	28.8	Feb. 27	21.2
Mar. 25	20.7	Mar. 28 P	33.6	Mar. 25	21.0
1904 Jan. 23	31.9	Nov. 15	23.4	Mar. 25 P	21.9
Jan. 23 P	32.1	Nov. 17 P	25.4	Sep. 6 P	22.2
Feb. 9	22.4	1914 Mar. 29	23.7	Sep. 7	21.3
Feb. 9 P	23.0	Mar. 29 P	24.4	Nov. 17	22.2
Mar. 4	29.7	1915 Jan. 8	22.6	Nov. 17 P	22.9
Mar. 4 P	30.1	Jan. 8 P	23.0	1927 Jan. 23	29.6
Mar. 8	26.2	Feb. 3	30.9	Jan. 23 P	29.7
Mar. 8 P	26.4	Feb. 3 P	31.6	Feb. 26	21.6
Mar. 24	21.0	Dec. 19	25.8	Mar. 22	24.0
Apr. 2 P	25.1	1916 Jan. 3	23.6	May 20	21.1
1905 Mar. 11	22.6	Mar. 23	22.4	May 20 P	21.4
Mar. 11 P	23.6	Mar. 29	25.0	Oct. 21	22.2
Mar. 22 P	32.2	1917 Jan. 23	27.2	Nov. 19	21.2
Dec. 4	26.3	Jan. 23 P	28.4	Nov. 19 P	21.4
Dec. 4 P	26.7	Mar. 13	26.2	Nov. 29	23.1
1906 Jan. 24	21.6	Mar. 13 P	26.3	Dec. 2	23.0
Jan. 24 P	21.8	1918 Feb. 16	21.5	Dec. 14 P	30.4
Apr. 1	21.5	Feb. 21	30.3	Dec. 15	28.2
Apr. 1 P	22.0	Feb. 27	22.2	1928 Mar. 31	22.5
1907 Jan. 15	24.3	Mar. 15	28.0	Mar. 31 P	22.6
Jan. 20	26.4	Mar. 15 P	29.0	May 1	23.6
Jan. 20 P	26.5	1919 Jan. 3	25.6	May 1 P	24.9
Mar. 15	38.3	Jan. 3 P	26.0	1929 Jan. 20	23.0
Mar. 15 P	38.7	May 12	20.7	Jan. 20 P	23.2
Mar. 20	24.2	Nov. 27	22.4	Feb. 27	24.6
Mar. 20 P	25.6	Nov. 27 P	23.2	Feb. 27 P	25.3
Dec. 24 P	21.9	1920 Mar. 13	25.2	Mar. 7	21.2
Dec. 25	21.4	Mar. 13 P	28.4	Mar. 7 P	21.9
1908 Jan. 14 P	23.5	Mar. 18	22.0	Oct. 3 P	23.9
Feb. 16 P	33.9	1921 Mar. 4 a	18.8	Oct. 4	22.4
Mar. 3 P	23.7	Nov. 29	27.6	Nov. 19	23.4
Mar. 8 P	24.1	Nov. 29 P	28.6	Nov. 19 P	23.7
Mar. 20 P	30.5	Dec. 25	24.4	1930 Feb. 27	23.7
1909 Feb. 17	22.3	1922 Mar. 16	21.5	Feb. 27 P	23.9
Feb. 17 P	22.5	Mar. 16 P	21.6	1931 Apr. 4 P	24.6
Feb. 25	25.5	Apr. 15 P	23.5	Apr. 5	23.4
Feb. 25 P	25.6	Apr. 16	23.1	Dec. 14 P	21.5
May 2 P	25.4	1923 Mar. 14	20.7	Dec. 15	21.3
1910 Jan. 19	25.2	May 13	21.8	1932 Jan. 31	21.2
Jan. 19 P	26.0	May 13 P	22.5	Jan. 31 P	21.4
Jan. 22	21.2	Dec. 24	21.0	Feb. 5 P	22.2
Mar. 1 P	25.2	Dec. 29	20.7	Feb. 6	20.9
Mar. 2	24.8	Dec. 29 P	21.4	Mar. 29-30	21.2
Mar. 8	21.6	1924 Jan. 4	30.4	Mar. 29 P	21.8
1911 Jan. 15 P	27.0	Jan. 4 P	30.6	Apr. 1 P	23.8
Jan. 31	28.2	Jan. 13	21.2	Apr. 2	22.7
Jan. 31 P	28.4	Jan. 18	22.2	1933 Mar. 15 P	29.6
Sep. 16	22.5	Mar. 30	31.5	Mar. 16	28.9
Sep. 16 P	22.9	Mar. 30 P	32.4	Mar. 22	23.1
1912 Mar. 16 P	22.2	May 10	22.3	1934 Jan. 8	21.7
Mar. 17	21.1	May 13	29.4	Jan. 8 P	22.3
Mar. 22 P	31.3	May 13 P	29.6	Mar. 6	22.4
Mar. 31	20.7	June 30	23.3	Mar. 6 P	25.8
Apr. 3	22.4	June 30 P	23.7		
Apr. 3 P	23.2	Oct. 1	23.1		

a = below base

Note: Unless designated by "P" (momentary peak), gage-height values are single daily readings usually taken in morning.

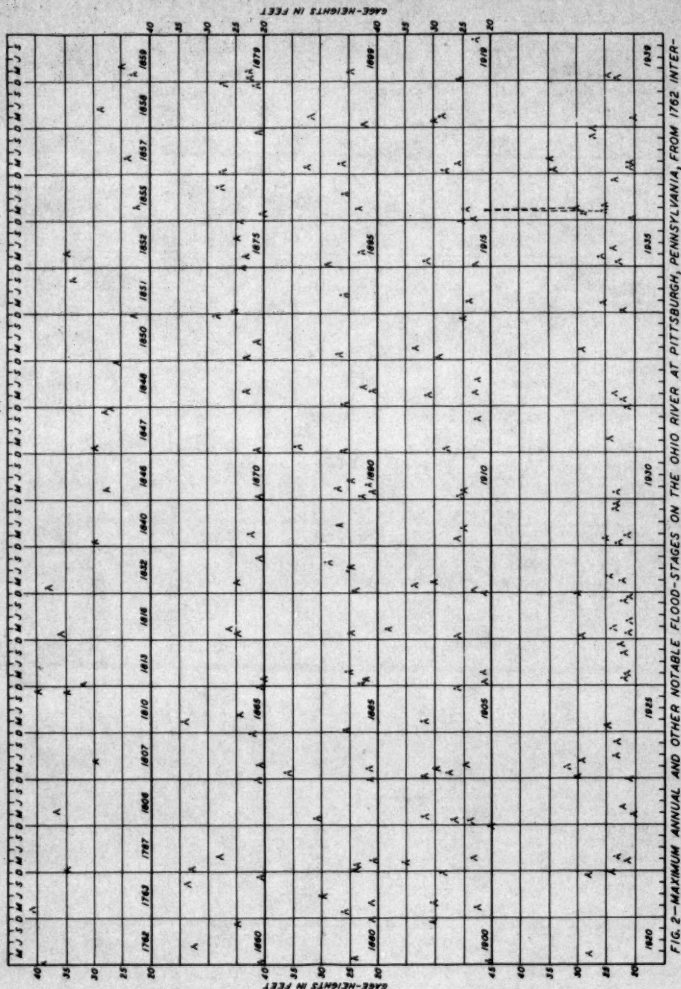


FIG. 2—MAXIMUM ANNUAL AND OTHER NOTABLE FLOOD-STAGES ON THE OHIO RIVER AT PITTSBURGH, PENNSYLVANIA, FROM 1762 INTERMITTENTLY TO 1857; THENCE CONTINUOUSLY TO 1939

[References: U. S. Geol. Surv. W.-S. Paper 771, pp. 162-163; 838, p. 639; U. S. Geath. Bureau's records of river-stages]

Table 3-A--United States Weather Bureau records of
Ohio River stages at Pittsburgh, Pennsylvania

Date	Gage-height	Date	Gage-height
	feet		feet
1934 Mar. 6	25.8	1937 Jan. 19	28.1
1935 Jan. 22	23.0	Jan. 23	22.9
Mar. 13	26.3	Jan. 26	34.5
May 8	24.0	Feb. 10	21.2
1936 Jan. 10	20.8	Mar. 22	21.2
Feb. 28	29.2	Apr. 27	35.1
Mar. 13	25.7	Oct. 29	27.8
Mar. 18	46.0	Dec. 19	27.5
Mar. 26	30.6	1938 Feb. 21	20.1
Apr. 7	25.5	1939 Jan. 31	23.3
Nov. 5	23.7	Feb. 4	24.9
1937 Jan. 11	24.6	Feb. 5	20.9

at the head of the Ohio, led to the keeping of early records of flood-stages. Observations of river-stages were later taken over by the United States Weather Bureau and the Geological Survey. Table 2 lists in chronological order the maximum annual flood-stages near the site of the old fort, the objective of Braddock's Expedition, which provided a test of George Washington's early leadership.

Figure 1 shows the maximum yearly and other notable flood-stages, including the early years of broken record, and 92 years of continuous record. While it is well known that many changes have occurred in the river-channel since early Colonial times, both as to enlarging or clearing some parts of the channel, and also filling in or occupying portions of the river-valley formerly subject to frequent overflow, it is interesting to note the outstanding stages. It appears that the first two yearly maxima definitely recorded were 39.2 and 41.2 feet in January 1762 and March 1763, respectively, followed by 40.2 in November 1810 as compared with the 36.5 feet of February 1884, later superseded by the 38.7 feet of March 1907, the recognized 90-year maximum until the unprecedented flood of March 1936, when the gage-reading attained 46.0 feet. The tangible damages resulting from the Pennsylvania floods, estimated at more than \$200,000,000, most of which was along the Ohio and its tributaries, to say nothing of the intangibles and the known loss of life, might have gone far toward providing the necessary storage for flood-protection and regulation under a well-conceived, coordinated, and completed conservation-program.

Upper Mississippi Valley floods--The flood-peaks attained in the Upper Mississippi Valley exclusive of the Ohio Basin were generally much lower than those considered in the four regions above described. This fact is represented graphically in Figure 2 on which the Myers scale percentage, indicative of flood-intensities, range generally from three to 15, or occasionally reaching 25, in contrast with the 10 to 50 per cent prevailing or to be expected in much of the eastern portion of the United States. Outstanding among the Myers scale-values westward from the Upper Mississippi River is the 72 per cent in southeastern Iowa, resulting from an intense summer storm or cloud-burst on Devils' Creek, draining only 143 square miles, but discharging a peak-flow of some 86,000 c.f.s. Compared on the basis of Myers scale-ratings, there is marked similarity apparent between Upper Mississippi River and the Great Lakes drainage-areas, due undoubtedly to the great infiltration-capacities of the glaciated soils, and to the gentle gradients, more than to the rainfall-rates and total volumes.

South-Central States floods--A wide range of physical conditions, particularly as to soil-types, topography, temperature, amount of rainfall and its distribution, accounts for the wide variation in observed flood-intensities as depicted on Figure 2. The range of Myers scale-percentages from less than 10 to more than 200 in Texas presents only a phase of the situation; the frequency of occurrence is not shown except by implication--for example, by recurrence of a given number within a region.

Tropical storms originating about the West Indies, and bearing westward sufficiently to strike inland through Texas, presumably include some of the most energetic storm-centers. They may not achieve their maximum rates nor amounts of precipitation along the coast-line, according to previous experience, but are more likely to do so while crossing the barrier known as the Balcones Fault, some 60 to 100 miles inland. From the Rio Grande to the Canadian River, so many unusually high flood-peaks have been recorded at one or more stations during recent years as to define this region as an outstanding flood-problem area. The contrast afforded in the semiarid sections by the parched soil with desert types of vegetation predominating, and the torrential

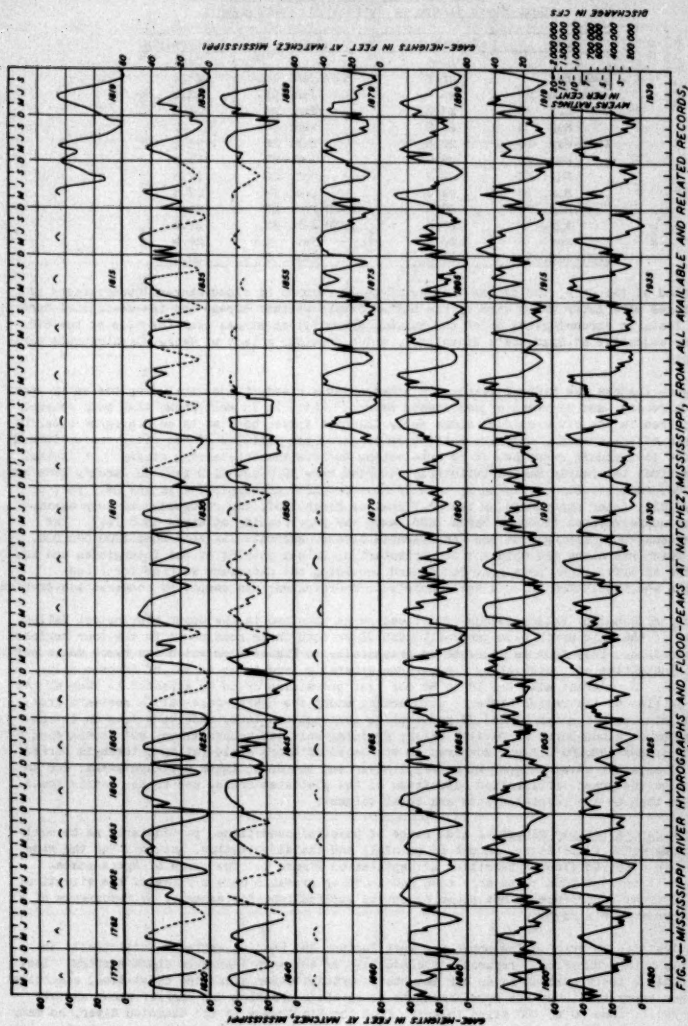


FIG. 3.—MISSISSIPPI RIVER HYDROGRAPHS AND FLOOD-PEAKS AT NATCHEZ, MISSISSIPPI, FROM ALL AVAILABLE AND RELATED RECORDS, 1770 TO 1839, INTERMITTENTLY (BROKEN LINES INDICATE DERIVED AND ESTIMATED PORTIONS OF THE HYDROGRAPHS)

[References: Humphreys and Abbott's Report on the Mississippi River, 1861 (Figs. 5, 6, and 8); Mississippi River Commission Progress-Report, 1891 (App. F, Pl. 3), and their later publications; U. S. Weather Bureau's records of rainfall, river-stages, and flood-phenomena]

flows which wreak such havoc over extensive areas subject to inundation and erosion or sedimentation, indicate the need for retaining a larger percentage, if not all, of the moisture in the soil and in storage, either surface or underground, for beneficial use.

Figure 3 is submitted as indicative of the Mississippi River stages observed at Natchez, Mississippi, with peaks recorded as early as 1770, and intermittently thereafter until 1802, then with at least partial hydrographs including the peaks for most years until 1872, and continuous daily records thereafter, comprising some 105 years of daily records. Necessarily there is much uncertainty as to the stage-discharge relation throughout the record-period. The scale of discharge in c.f.s. following the last yearly hydrograph is a fair average for the latest decade of record and perhaps longer, but may be quite divergent from the correct scale for much earlier periods, before the levee-systems were completed, or secured against recurrent crevasses. For example, the gage-height of 46.2 corresponding to a discharge of 1,520,000 c.f.s. [Stages and discharge-observations, Lower Valley of the Mississippi River; Mississippi River Commission, 1937] on March 30, 1891, was exceeded by four feet or more for equal discharges during the past 15 years or so.

Comparing the April-May hydrographs for the years 1922 and 1927, the difference is not so much in flood-peaks attained--55.2 and 56.85 feet, respectively--as for duration of 40-foot or higher flood-stages, those of 1927 having begun as early as January, if not the preceding November, to be temporarily checked by low temperatures through December, and afterward extending from January to mid-July, as compared with the 1922 flood-rise which began in April and ended in June. The 58-foot gage-height attained on February 21, 1937, was ten feet above that of 1782, noted as "the highest known to that date."

Marked deficiencies in Mississippi River stages at Natchez occurred in both 1889 and 1936, even though the Ohio headwaters and the rivers eastward sustained some of their outstandingly high flood-seasons. Other years of marked deficiency were 1829, 1839, 1872, 1895-96, 1901-02, 1925-26, 1931, and 1934, in every case followed by hydrographs well above normal within the next year or two thereafter, as though one element in flood-producing storms may have been delayed delivery, or deferred precipitation and consequently uninterrupted atmospheric storage of moisture during the preceding drought period which, after all, constitutes a drought.

The maximum floods of the Lower Mississippi, rating generally from 13 to 21 on Myers scale, may be regarded as integrated, weighted averages of the ratings for tributaries; for example, the ratings of about 40 along the Ohio, of 8 to 10 along the Upper Mississippi and the Missouri, of 20 to 30 along the White and St. Francis, 11 for the Lower Arkansas, and 10 to 15 on the Yazoo as shown in Figure 2, each in its turn, to produce the ratings of 13 to 21 per cent of the main river below Cairo. There seems to be at least a chance relationship afforded by the early estimates of runoff-factors or average percentages of rainfall appearing as stream-flow, for the entire Mississippi Basin, ranging from 51.5 per cent for the Central Valley to 30 per cent for the Ohio, 22 for the Red, and about 15 per cent for the Missouri and Arkansas River systems [United States Weather Bureau Bulletin E, 1897, "Floods of the Mississippi River," p. 27], the resulting weighted average being 24.7 per cent. The 672,000 c.f.s. estimated average or normal discharge from the Mississippi as there recorded is fairly close to both the 43-year and 7-year averages up to and including 1934, which are 650,000 and 620,000 c.f.s., respectively. The influence of the higher than normal discharges during the four-year period including 1938, when evaluated, will evidently bring these averages into very close agreement.

Rocky Mountain floods--Flood-peak ratings in the Rocky Mountain Region, where expressed in percentage on the Myers scale, range from about 2 to 20 generally, but occasionally attaining to 40 or even higher values due to cloud-bursts on steep slopes, as shown on Figure 2 for central Colorado. Necessarily the floods from melting snow are considerable items throughout the high mountainous areas from Montana to Arizona and New Mexico. Due to the sparse distribution of gaging-stations, and to their brief or intermittent records generally, we are led to the conclusion that many more of the higher flood-ratings have actually occurred without official observations or records other than the vestiges of high-water marks, and many of these have never been evaluated.

One of the characteristics of desert areas is the irregular and wasteful distribution of moisture; sharp torrential downpours for brief periods causing such disturbance and erosion of the soil-mantle as to reduce infiltration-capacity, fertility, and consequently vegetal cover except for the hardier types. Whenever dense woods or other protective canopies prevail, as in the higher altitudes of some of the mountainous regions, the lower temperatures and associated evaporation-rates plus the greater infiltration induced by dense vegetal cover with possibly some excess of rain due to altitude, all serve to make the transition from desert conditions at

mountain-base to at least semihumid or even humid conditions at mountain-crests.

Denudation of vegetal cover, especially in fire-swept areas, has had a marked effect on both the frequency and magnitude as well as the erosive power of storm-runoff, so that new records are being established at an alarming rate in many regions. Conservation and regulatory measures initiated thus far have proved their effectiveness in partially restoring the original water-holding capacities, or even providing complete regulation and utilization of the water-resources of certain river-systems. Even on such areas the problems of runoff, erosion, and sedimentation continue in local prominence, due to their relation to the life and useful capacities of reservoirs and channels, both natural and artificial.

Floods in Pacific Coastal rivers--Due to either altitude or latitude, runoff from melting snow- or ice-accumulations plays a prominent part in the genesis of floods on the headwaters of most of the Pacific Coastal river-systems. A combination of heavy precipitation and snow-melt may account for the maximum observed flood-peaks from large drainage-areas, but still higher ratings are attained occasionally due to intense local storms and cloud-bursts covering smaller areas. The step-by-step variations observed along the Snake River to its junction with the Columbia together with the ratings from there on to the coast disclose some of the prominent rainfall- and runoff-characteristics of the successive tributaries. It is remarkable how nearly comparable are the flood-peaks around San Diego and Los Angeles under deficient annual rainfall-conditions as compared with the more humid regions of the Upper Sacramento and the very humid regions of southwestern Oregon and Washington. In the latter areas, no doubt the dense vegetal cover supported by the dependable rainfall plays an important part toward induction of water into the soil and regulation by detention, interception, or other retarding processes. The intensive developments along the coastal region have brought more prominently into relief the hazards impending, and have demanded adequate measures to cope with such situations as developed in March 1938, for example, in Southern California, where tangible damages inflicted were of the order of \$80,000,000. A considerable number of the maximum ratings recorded on Figure 2 in the Los Angeles Region resulted from that record-breaking storm. Nearly comparable floods had been observed occasionally at one or more stations, but never before since installation of modern and improved gaging-equipment or facilities, was such an extensive area covered by a single storm of equal intensities.

Soil Conservation Service,
Washington, D. C.

SOME GENERAL OBSERVATIONS OF PHYSIOGRAPHIC AND CLIMATIC INFLUENCES ON FLOODS

W. G. Hoyt and W. B. Langbein

The magnitude of flood-runoff and the degree to which it concentrates in river-channels with respect to time is known to vary within wide limits. To a considerable extent these variations relate to the physiographic and edaphic features of the drainage-basins as they have been developed by the geologic and climatic history of the particular province in which they are located. Although storms of high intensity occur throughout the United States, the runoff therefrom has been observed to have certain inherent characteristics in wet or humid areas that are different from those in arid or semiarid regions even though the laws governing the flow of water either over ground or in river-channels are universal in application. Essential features of flood-behavior in wet or humid areas where stream-flow is sustained throughout the year and river-channels and valleys are comparatively well defined and permanent, differ from those in arid or semiarid regions where stream-flow is very erratic and flashy and the channels are formed largely by occasional intense runoff rather than the slow and orderly development by the continuous occupancy by flowing water. Moreover the flood-problem in areas where a part of the precipitation occurs as snow differs from that in areas where all the precipitation occurs as rain. Furthermore, in areas where snow does occur there seems to be a wide range in flood-runoff characteristics depending upon the temperature in and altitude of the particular zone. Some of the different flood-characteristics as they relate to total runoff and the concentration thereof are described herein and possible reasons therefor are related to conditions which seem to be more or less inherent in particular physiographic and climatic provinces.

Flood-events may be analyzed with respect to three fundamental factors, namely: (1) Supply, whether in the form of rain or snow depending on temperature and physiographic features; (2) edaphic conditions; (3) basin- and channel-characteristics. Each of these factors is influenced by climate and physiography.

The nature of the supply is essentially a climatic characteristic but depends in part upon the effect of physiography as it influences both precipitation and temperature. The effect of altitude in inducing precipitation during invasions of moist air-masses and in decreasing temperature are well known. These physiographic influences may be evaluated in studies of flood-behavior inasmuch as the supply is the primary factor underlying all flood-events.

The ability of the soil and vegetation to serve as agencies for the disposal of potential flood-water is in a large sense a climatic factor. It depends not only upon the composition and gradation of the soil and the density and type of the vegetation but also upon the degree to which their absorptive capacity has been utilized. All of these factors are largely reflections of their particular climatic environment experiencing seasonal changes in accordance with the established climatic regimen. Two principal factors that influence the soil and vegetal characteristics are those of precipitation and temperature. Thus it is observed that not only do precipitation and temperature affect the supply but also the ability of the soil to serve as a vehicle for its disposal.

Ultimately a portion of the supply reaches the channel-phase where the flood is experienced. The storage-effects of the channel serve to prolong the runoff and generally there is no loss of water unless the channel invert or stage is above the ground-water plane.

The flood-stage at any given point is determined not only by the rate and volume of inflow into the upstream tributary channels but by their arrangement and their discharge-storage characteristics. These sensibly permanent basin-characteristics were determined largely by the past geologic and climatic history of the region and by the prevailing climate. The flood-stages would seem to be not only related to the contemporaneous upstream conditions of weather but also to the accumulated effects of all past floods.

Geologic evidences suggest that a significant portion of channel-development takes place during flood-experiences. Thus it seems that climatic and physiographic factors underlie the channel-phase as well as the supply and the edaphic phases of flood-events.

Inspection of the climatic regimen prevailing in the United States suggests two principal methods of classification with respect to flood-behavior. First, classification may be made on the basis of mean annual rainfall which would divide the country broadly into the eastern humid region and the western arid or semiarid region and, secondly, classification may be made on the basis of snowfall. Figure 1 shows the normal climatic regimen of the United States according to Thornthwaite and Figure 2 shows areas in the United States where the mean annual depth of snowfall is less than 20 inches, from 20 to 60 inches, and above 60 inches.

The humid east presents generally uniform conditions but may be divided into two regions on the basis of temperature, that is, northern and southern. The west, on the other hand, largely due to its great differences in altitude and location with respect to the Pacific Ocean over which most of the western flood-producing storms originate, is a region where material variations in climate occur in relatively short distances and generalizations are difficult and subject to error. Nevertheless, it would seem that certain regional classifications with respect to distribution of rainfall and snow as they influence flood-behavior can be made.

Figure 3 shows three typical flood-hydrographs, two of which, namely, the James River and the Frio River, resulted from rain and the Kootenai River from melting snow.

In problems related to storage and retention of water either by means of reservoirs or through the medium of land-use practices or in areas where flood-runoff eventually accumulates in river-channels and overflows wide flood-plains, a knowledge of total volume of flow during flood-periods is essential. In problems relating to flood-forecasting, the design of spillways, bridge openings, channels, and flood-way capacities and other problems relating to the dynamic action of water in stream-channels, the extent to which the flood-water is concentrated with respect to time is of paramount importance.

With respect to the relation between drainage-area and the volume of runoff associated with a single flood-rise, two factors appear of major influence. First is the observation that rainfall during a storm is not uniform over wide areas, generally decreasing in amount about a central area of maximum precipitation. Thus the mean depth of precipitation during a given storm decreases as large areas are encompassed.

The second factor is the increase in the time-base of flood-hydrographs with increased drainage-areas. An examination of 33 outstanding storms in the northeastern United States indi-

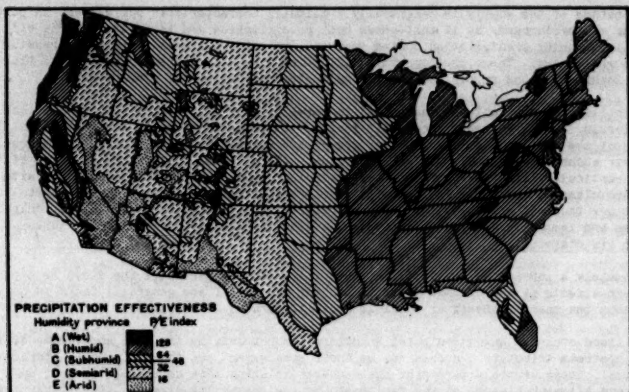


FIG. 1 - NORMAL CLIMATIC REGIMEN OF THE UNITED STATES BY C.W. THORNTWHAITE

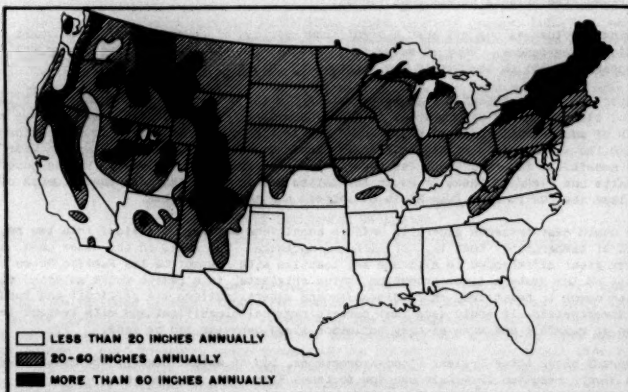


FIG. 2 - AVERAGE ANNUAL SNOWFALL (FROM DATA BY U.S. WEATHER BUREAU)

cates that a given depth of rainfall is associated with shorter time-periods for smaller areas and longer periods for larger areas. In other words, under average conditions the time-depth rainfall relations are such that for equal storm-areas longer periods of precipitation are usually associated with greater average depth of precipitation. The relationship shown with respect to areas is somewhat comparable with the square-root variations in flood-time base as outlined by the Boston Society of Civil Engineers. Thus outstanding floods may be expected to disclose some uniformity with respect to volume regardless of variations in drainage-area, even though their concentration-factors may differ widely. Comparison of the volume of runoff of major floods in the several climatic and physiographic provinces may therefore be used as an index of the potential supplies available for flood-runoff and characteristic of each region.

Based on a preliminary study of the total runoff reaching stream-channels during flood-periods, either as direct surface-runoff or as subsurface flow with a responsiveness approaching that of direct surface-runoff, it appears that in parts of the United States there is a fairly

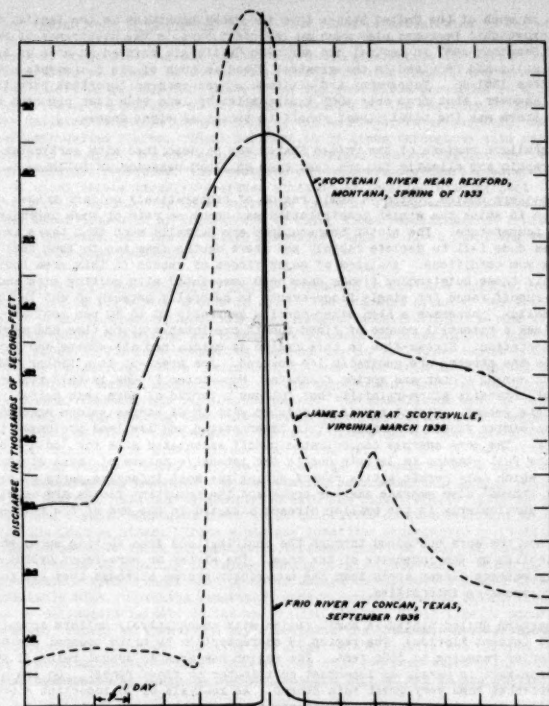


FIG. 3—TYPES OF FLOOD-HYDROGRAPHS

well-defined limit to the runoff expressed in inches over the entire drainage-area that may reasonably be expected in any particular climatic zone during a single flood-rise. Although time has not permitted analyses of the direct runoff of all floods of record, it appears that in areas or during periods when runoff from melting snow is not involved the total runoff as defined above during individual flood-events has rarely exceeded eight to ten inches whereas in areas or periods where runoff from melting snow is involved a flood-runoff exceeding eight to ten inches over the drainage-basin is of somewhat common occurrence. The character of the storms associated with these floods has varied greatly between short intense storms for small drainage-basins and widely extended general rainfall covering many days and marked by several comparatively intense storm-periods. Also, the flood-rises varied from sharp intense peaks for small basins to relatively flat rises extending over many days for the larger basins.

A condition which may have an effect upon the areal extent of the runoff relates to altitude and topographic aspects as they affect rainfall. During the storm-period ending January 25, 1937, which resulted in the outstanding Ohio River flood there was an average of 12.85 inches of rain over an area exceeding 200,000 square miles tributary to a single channel-outlet, the Ohio River at Cairo, Illinois. Such wide-spread storms resulting in great accumulations of water in one channel apparently can not occur in those parts of the United States where rainfall is closely related to altitude, the storm-shadows of mountains, and the source of supply. The total runoff passing Cairo as the result of the 1937 storm was approximately 96,000,000 acre-feet or 8.9 inches over the entire area of 203,000 square miles. No such accumulation of flood-water

seems possible in much of the United States from the Rocky Mountains to the Pacific Ocean where altitude and topographic features play such an important part in the occurrence of rain. The great storm of December 1937 in central and northern California covered an area of approximately 109,000 square miles and resulted in the greatest flood in such of the Sacramento and San Joaquin river-basins since 1861-62. Topography and altitude played such an important part in the occurrence of rain, however, that from only 4000 square miles or less than four per cent of the area covered by the storm was the total direct runoff in excess of eight inches.

Broad generalized regions of the United States may be described with particular reference to the physiographic and climatic factors that bear on flood-behavior as follows:

(1) Northeastern United States--A humid region of comparatively uniform annual distribution of precipitation in which the winter precipitation may occur as rain or snow depending on small differences in temperature. The winter temperatures are normally such that there is a tendency for such snow as does fall to deplete rapidly and where depths from two to four feet represent essentially maximum conditions. Analyses of major floods of record in this area indicate that almost invariably these outstanding floods have been associated with melting snow and that the limiting flood-runoff range for single flood-events is generally between 10 and 15 inches. The snow, though shallow, possesses a high water-density generally 20 to 30 per cent which constitutes at all times a potential source of flood-runoff predictable as to time and magnitude only by constant observation. Stream-flow in this region is maintained all winter and in the northern and higher parts the streams are generally ice-covered. Ice break-up is a factor that aggravates flood-conditions during winter and spring freshets. Non-winter floods in this region occur only as the result of intensive storm-rainfall that follows a period of more than normal rains which serve to prime the ground. Direct runoff associated with these storms seldom exceeds eight to ten inches. Non-winter floods generally attain lower stages and are less prolonged than winter or spring floods. The more sharply concentrated runoff associated with the "cold-front storms" of the summer and fall seasons is largely due to the intensive nature of these storms and to soil-conditions which only permit active runoff during the most intensive parts of the storm. The "cold-front storms" also embrace smaller areas and the resultant floods are usually severe in local areas, particularly in the smaller streams situated in the eye of the rain-storms.

Winter floods are more sustained through the contributions from melting snow, which rate of melting is controlled by the intensity of the thaw. The winter or warm-front storms within this region generally embrace larger areas than the non-winter storms although they are rarely accompanied by record-breaking intensities.

(2) Southeastern United States--A humid region with comparatively uniform annual distribution of rainfall (except Florida). The region is characterized by broad coastal plains with relief in the interior reaching to 5000 feet. The region has greater annual rainfall than the northeast but snow-melt is rarely an important contributor to flood-runoff. On the other hand, the region experiences some very great rain-storms. An analysis of 33 important storms of the northeastern United States and 40 important storms in the southeastern United States indicates the wide variations in storm-rainfall that exists between these two regions, the rainfall during the major storms of the southeast exceeding the rainfall during the major storms of the northeast. A partial study of runoff associated with some major floods in the southeastern region, however, shows eight inches or less as compared with eight to ten inches during major floods in the northeast that are associated with rainfall alone and 10 to 15 inches when snow-melt is involved.

(3) The Great Plains--A subhumid to semiarid grass-land region of summer rainfall lying generally west of the 96th meridian, rising uniformly to about 5000 feet at the foothills of the Rocky Mountains. Except during intensive cloudburst-storms, no stream-flow originates in this region where rainfall is generally insufficient to meet the consumptive requirements of evaporation and vegetal transpiration. Aside from the northern Great Plains, snow rarely occurs in amounts sufficient to be an important contributor to flood-runoff. This region is, however, characterized by its intense summer storms which produce severe floods and which may or may not be parts of more general wide-spread storms. Geological Survey Water-Supply Paper 796B, "Flood on Republican and Kansas rivers, May and June 1935," is descriptive of a major flood in the Great Plains. The storm causing this flood embraced nearly 80,000 square miles of five days' duration, the greatest part falling in one day. Although precipitation extended to a maximum of 15 inches, runoff expressed in inches over the basin was not large when compared with runoff from the humid eastern regions. Maximum measured runoff from an area whose average rainfall was about seven inches, was only about one inch. Low volumes of runoff appear to be characteristic of semiarid regions.

(4) United States west of the Great Plains--The flood-potentialities of the western part of the United States are intimately associated with physiography which in turn varies so greatly that delineation of broad areas having similar flood-characteristics is impossible. Royce J. Tipton [Characteristic of floods in the Southern Rocky Mountain Region, Trans. Amer. Geophys. Union, July 1937, part 2, pp. 592-600] shows three distinct flood-provinces in a relatively small area along the eastern slopes of the Rocky Mountains in the vicinity of Denver. Similar conditions are believed to obtain through most of the mountain, inter-mountain, and coastal section of the western United States. Exact delineation of areas throughout this region await the results of detailed studies. In the meantime certain flood-characteristics may be related to particular physiographic provinces, the locations of which are necessarily more or less generalized but all of which relate largely to either altitude or location with respect to mountain masses and the Pacific Ocean. The three principal types of floods are those resulting from melting snow either associated with or independent of rain, those resulting from prolonged rainfall of several days' duration, and the so-called cloudburst-type of flood resulting from rainfall of short duration but of high intensity.

Floods from melting snow in Western States--Depending on altitude and latitude, snow gradually accumulates during the winter months in all of the mountain areas of the West with the possible exception of the central and southern coast-ranges in California. At the higher altitudes, mean temperatures during the spring and summer are so close to freezing that snow depletes slowly and areas above about 10,000 feet, depending somewhat on the latitude, can be considered as essentially non-flood producing. Snow-fields at altitudes lower than about 10,000 feet constitute the principal source of annual spring floods in the major basins draining the slopes of the Rocky, Sierra Nevada, Cascade, and Olympic mountains. The snow-fields melt at rates proportional to the intensity of the thawing temperature which increases as the season advances. The snow-melt produces an annual flood, the height of which is determined by the equivalent depth of water in storage at the close of the winter season and to the rate of rise in temperature. The Kootenai River graph on Figure 3 shows a typical flood-rise from melting snow not associated with any material contemporaneous rainfall. In the Pacific northwest, and to some extent at lower altitudes in the Sierras, rain may be associated with the flood-runoff. This is especially true in the Cascades and Olympic mountains where large quantities of snow are rapidly converted into flood-water by the Chinook winds. These winds are sometimes accompanied by rainfall. Records of outstanding floods under these circumstances indicate that the combined runoff from the rain and snow ranges from 15 to possibly 30 inches during single flood-events which is an approximate measure of the maximum flood-runoff that probably occurs in the United States from drainage-areas of appreciable size. Speaking generally, western areas in which floods from melting snow originate can be delineated largely on the basis of altitude. Their time of occurrence is relatively uniform and, except as warm rains may complicate the problem, their probable maximum discharge is predictable in advance. Omitting the areas in the Pacific and central northwest where Chinook winds predominate, flood-runoff from melting snow and associated rains during single flood-events is comparable to those in the northeastern part of the United States.

Floods from rain in the Western United States--In the West, as elsewhere, the two general types of rain-storms, that is, the prolonged type of low intensity and the short-duration type of high intensity, result in floods of distinctly different characteristics. Speaking generally again, in the humid east floods of these two types may occur at any location and more or less commonly through the year. In the west their location is more or less fixed by the relation of the areas to mountain masses and the Pacific Ocean and the times of occurrence relate largely to the seasons.

From November through June, storm-disturbances move inland from the Pacific and Pacific northwest resulting in precipitation which is confined largely to the western slopes of the several parallel mountain ranges extending from the coast-range and the Olympics to the Rocky Mountains. On the eastern slopes of the ranges the precipitation is generally less and in the great intervening valleys such as the Central Valley in California and the inter-mountain area in Nevada and Utah may be relatively insignificant even during wide-spread disturbances. Moreover, at the higher altitudes at least in the Sierra Nevada Mountains the precipitation which falls as rain decreases and the higher parts of these western slopes are not flood-producing.

The cloudburst-type of flood common throughout the west but more especially in the semiarid portions from the Sierra Nevada to the eastern foothills of the Rocky Mountains occur generally in the summer months either along mountain fronts where moisture-laden air is deflected upward causing rapid condensation or of the thunder-storm type not associated with mountain masses. Neither of these types of floods is predictable as to time and quantity. In general, they embrace but small areas. The resulting runoff reaches peaks of high intensity but the total runoff expressed in inches over the area is relatively small.

In addition to physiography as it affects the occurrence of rain and snow, temperature, and precipitation as they combine to form distinct climatic provinces, each with their peculiar edaphic conditions as related to infiltration- and retention-capacities, have a marked effect on the probable magnitude of flood-runoff. It seems axiomatic that other things being the same and disregarding geologic differences the capacity of the drainage-area to absorb and retain precipitation will depend largely upon the normal distribution and magnitude of the precipitation. Disregarding seasonal differences which may temporarily change a semiarid region to a humid region and vice versa, the inherent ability of the soil and its vegetal canopy to absorb and retain water will vary inversely with the magnitude and the occurrence of rain. It seems reasonable to expect that in an area which normally would be classified as wet or humid, where sufficient precipitation occurs at intervals throughout the year to maintain ground-water above the stream-channels so that stream-flow is sustained at all times and soil-moisture is available sufficient for the growth of vegetation, the ability of the soil to absorb rainfall would normally be less than in a climatic province where rainfall is either infrequent or entirely absent for long periods of time and where normal ground-water is far below the stream-beds and where soil-moisture is insufficient for the growth of vegetation without the artificial application of water. Studies which have been made of the relations between rainfall and runoff during outstanding storm-periods in humid areas such as drained by the Ohio, St. Lawrence, and North-Atlantic-Coast streams and in the semiarid or subhumid regions such as are drained by the Sacramento, San Joaquin, and South-Pacific-Coast streams indicate that under fairly comparable storm-conditions the total direct flood-runoff in the humid east is largely a function of the total rainfall, that is, infiltration and retention during outstanding flood-periods are relatively insignificant whereas in the arid, semiarid, and possibly subhumid regions of the west, the total runoff over large areas is relatively small and has little or no relation to the storm-precipitation, being more a function of the ability of the large areas to retain the infiltrated water. For example, residuals or differences between rainfall and runoff during outstanding storms in the Ohio Valley, Pennsylvania, New York, and New England have averaged between two and four inches under rain-storm experiences of from 10 to 20 inches whereas residuals in California during the outstanding storms and floods of December 1937 and March 1938 have ranged from 10 to as much as 20 inches with storm-experiences of from 15 to 28 inches--residuals as low as four inches being the exception, not the rule. To those who are acquainted with the flood-producing possibilities of isolated storms of from 10 to 12 inches in humid areas, the absence of flood-runoff under single storm-experiences of the same magnitude on steep mountain slopes of parts of the southern coast-range is amazing. Similar studies have not been made in the Great Plains where the relative scarcity of rain-gages prevent the determination of the areal precipitation or in the Northwest and Rocky Mountain area where the wide-spread floods from large areas are influenced by runoff from melting snow, the magnitude of which can not be definitely determined with the information at hand. It is believed, however, that when complete analyses have been made, it will be found that there is a definite relation between infiltration, retention, and climatic zones. The total flood-runoff being a difference between the rainfall and the retention, a direct relation between the magnitude of the total flood-runoff and climatic zones should be indicated. There is need, as has been pointed out in the past, for the preparation of hydrologic maps in the United States which will indicate the seasonal values of the absorptive capacities of the ground.

Based on analyses of many major floods, especially those in the north-central, northeastern, middle Atlantic, and some in the North Pacific States and California, it appears that the amount of direct runoff that has occurred during single flood-rises of record has a fairly definite range for certain regions and that, except possibly for small drainage-basins, the total direct runoff has been about the same for the various sizes of drainage-areas in a particular region.

For example, direct runoff for some single major flood-rises in the Pacific northwest has ranged from about 14 to 29 inches. The runoff during these floods has been associated with melting snow and the upper limit probably represents approximate limits of direct runoff during major flood-rises in the United States. The next lower range seems to be from about 10 to 14 inches for floods associated with heavy rains and melting snow in the north-central and northeastern States, and for some floods in California without snow. From 4 to 10 inches represents the limits of single flood-events in much of the north-central, northeastern, and southeastern States when no melting snow is involved. In parts of the semiarid plains, upper limits seem to be about four inches. Analyses are not complete with reference to the runoff during single flood-rises in parts of Texas, the south-central, or the southwestern States.

When all the single floods of record have been analyzed, it is expected that their total direct runoff will be found to group more or less definitely into climatic and physiographic provinces. With the possible exception of very small areas, it is also expected that the limits of the runoff for any particular province will be about the same for all sizes of drainage-areas. It is also expected that through the hydrometeorological studies now being made by the Weather

Bureau and the Corps of Engineers the limits outlined herewith will be exceeded but that the derived limits will bear some relation to province and climatic zones.

Relative to the degree with which flood-runoff is concentrated with respect to time, there also seems to be certain characteristics which may be more or less related to physiographic and climatic provinces. Such studies as have been made of flood-hydrographs where snow was involved seem to indicate that, for the same total flood-runoff, the ratio between the peak-discharge and the total runoff is less when snow is involved than for floods resulting wholly from rain. Although, as has been indicated, the total runoff is almost invariably increased by the snow, the time element involved in the runoff is longer. For the same area it seems apparent that floods in periods when snow is present are less concentrated with respect to time than for floods when similar amounts of water are involved but all in the form of rain.

With regard to the concentration of flood-runoff resulting wholly from rain and in the magnitude of peak-discharges, there are wide variations. These variations seem to relate, among other things, to infiltration- and retention-capacities as modified by climatic differences. All seem to relate largely to the manner in which flood-runoff reaches stream-channels. Unfortunately, by and large, much of our present knowledge relating to the mechanics of flood-runoff from drainage-areas has been based on observations made in the north-central and northeastern parts of the United States where, relatively speaking, the greater proportion of the flood-runoff is essentially direct surface-runoff and infiltration-rates and retention-capacities over large areas during major flood-periods are known to be relatively small. As studies of flood-runoff have been extended to other parts of the United States, marked differences in flood-characteristics are noted. These differences seem to relate partly to the proportion of the total flood-runoff that reaches stream-channels as direct surface-runoff and the proportion that reaches stream-channels after passing through the ground. These proportions seem to vary with climatic provinces.

Studies of flood-hydrographs in the humid east indicate a rapid superimposing of a large amount of direct surface-runoff on a fairly large but uniform ground-water base.

Betram S. Barnes has pointed out that in the central part of the United States where stream-flow is also maintained throughout the year but outflow from ground-water is generally less than in the more humid parts of the east, studies of flood-hydrographs indicate that relatively less of the flood-runoff occurs as direct surface-runoff and that the hydrograph can be considered as built up of a low but uniform ground-water flow; a large accumulation of relatively slow-moving ground-water which gradually builds up to a medium high but long-extended hydrograph superimposed on which, but occurring during an earlier phase, is a relatively small amount of direct surface-runoff.

Flood-hydrograph analyses in arid and semiarid regions resulting from rain seem to have marked different characteristics than those in subhumid areas. These differences are characterized generally by an absence of any sustained base or ground-water flow at the beginning of the flood-water period, the rapid concentration of flood-runoff, extremely high peak-discharges, but relatively small total runoff on an areal basis. Difficulties are involved in the analyses of these so-called "flash" floods in that they originate in areas where there is a paucity of rain-gages and it is generally impossible to delineate the areal extent of the storm, its average intensity over the area, or the extent of the area that actually contributes direct surface-runoff. Although infiltration-rates are known to be high as indicated by the amount of storm-precipitation required to produce significant amounts of stream-flow, continued rain produces peak-discharges and degree of concentration with respect to time surpassing any normally observed in humid areas. This type of flood occurs most often in dry stream-channels and there seems to be no gradual building up of channel-storage and gradual drainage therefrom. The flood-waters seem to have their source in only a part of the drainage-basin and result in the passage downstream of a wall of water, the front slope of which is much steeper than the back. Such floods are essentially non-basin wide in character. Although the storm may be basin-wide in character, the infiltration-rates are apparently so large that only near storm-centers is direct runoff produced. In humid areas infiltration-rates are generally so low that basin-wide runoff is produced from relatively light wide-spread storms resulting in basin-wide supply to stream-channels, with the result that there is a gradual accumulation of water to a peak at a given point indicative of the time when inflow into the channel-system balances outflow, followed by a gradual draining out of remaining storage.

In other parts of the country that can be classified as semiarid in that all the precipitation occurs during a shorter winter season, flood-runoff characteristics have been disclosed that are different from those in either humid areas or the partial basin-floods just described.

In parts of these areas, especially the coast-range in Southern California, plot observations indicate an almost complete absence of direct surface-runoff under storm-experiences up to 24 inches with the rates exceeding one and one-half inches per hour for several hours. From drainage-basins as such, however, in these same areas there is accumulation of flood-runoff in channels of the magnitude observed in humid areas and with a degree of concentration equal to that of direct surface-runoff. Although the small plots may indicate the absence of direct runoff and the differences between rainfall and runoff an absorption of between 15 and 20 inches, there is a rapid passage of a part of the infiltrated water into stream-channels either through the relatively shallow earth-mantle or through the upper parts of the shattered bed-rock. To the extent that the observations and deductions are correct, the flood-hydrograph in these areas is composed largely of ground-water which has concentrated very quickly as to time superimposed on which is a small amount of direct runoff with irregularities closely following irregularities in the maximum rates of precipitation. This condition may also apply to other parts of the country where floods occur although studies on small areas indicate very high infiltration-capacities.

As with the total runoff, it is believed that when all major flood-rises have been analyzed it will be found that for basins of comparable size the degree to which the total direct runoff is concentrated within an interval of time, such as 24 hours, will have some relation to zones or provinces and that major floods associated with snow will have lower ratios than floods of equal runoff with no snow involved. The degree of concentration will be greater in arid and semiarid regions than in wet or humid regions and perhaps other characteristics may be segregated.

The problem of flood-forecasting is difficult to say the least and each variation in flood-characteristic presents added difficulties. In addition to a knowledge of the universal laws governing the flow of water in open channels, an intimate understanding is necessary of the mechanics of runoff as such. It is hoped that to the extent flood-characteristics can be localized, by zones or otherwise, the technique of forecasting can become simplified.

U. S. Geological Survey,
Washington, D. C., April 1939

RECENT ADVANCES IN APPLIED HYDROLOGY WITH REFERENCE TO FLOOD-FORECASTING

LeRoy K. Sherman

For nearly a century, engineers relied upon empirical formulas to express the rainfall-runoff relation. Good judgment and experience was required to approximate the effects of the complex variables intervening between rainfall and runoff. To the credit of many of these engineers, the history of their works has confirmed their judgment. It has not confirmed their formulas.

We have gradually bettered our ability to estimate the magnitude and frequency of floods. This has been due to the acquisition of stream-gaging records and to the rainfall-studies of Meyer, Yarnell, the Miami Conservancy District, and others. Improved statistical methods have helped. The development of the rational method improved the art of estimating runoff--especially for small sewered areas.

There is a wide gap between the work of the estimator and the forecaster. It is the difference between "sometime" and "day after tomorrow." A flood-estimate is the ability to state that "a flood-stage of 53 at Beardstown will be reached on an average of once in 20 years." A flood-forecast is the ability to correctly prophesy that "a flood-stage of not less than 53 feet will be reached three days hence at Beardstown." Fair estimates may be made with many data coupled with good statistical methods, even though we consider the interrelation between precipitation and runoff as merely fortuitous. A forecast can be presented only upon knowledge and application of definite natural laws.

About ten years ago, following the studies of Pettis, Hayford, and the Committee on Floods of the Boston Society of Civil Engineers, the importance of the hydrograph was recognized in rainfall-runoff investigations. In 1932, the unit-graph method was presented by Sherman and supplemented by Bernard, Horner, and many others. The rapid progress in hydrology has been due, in a large measure, to the organization and work of the Section of Hydrology of the American Geophysical Union. It has viewed hydrology on the basis of a natural science, not as an engineering empiricism. At the same time came the important work of the National Resources Committee and the practical researches by the United States Department of Agriculture. Both of them indicate public

recognition of the importance of water-conservation and control in accord with sound hydrologic principles.

Modern research has called for quantitative determinations. It has supplanted qualitative analysis and speculative philosophy excepting as the latter may be useful in preliminary hypothesis for the conduct of experiments or segregated observations. Scientific analysis simplified complex and so-called erratic phenomena. It has eliminated factors, real in themselves, but insignificant in totals. It has cancelled some concurrent elements. This study, still in active evolution, has definitely paved the way to reliable estimates of runoff, and it has opened the door to the possibility of forecasting floods.

We now know that time-distribution of runoff is a basin-characteristic and that, within certain limits, the ordinates of runoff of unit-hydrographs are proportional to the volumes of excess rain during the unit of time.

The estimate of excess rain, by use of an estimated coefficient of runoff, has long been used and long ago found unsatisfactory. It was recognized that runoff was not primarily a percentage of rainfall, although it might be conveniently expressed as such. It was known that runoff equals rainfall minus infiltration and other losses.

Forecasting requires a knowledge of the average infiltration-capacity of each component basin of a river-system. In 1935, Horton presented a method for computing the hydrograph of overland flow from the observed hydrograph of channel-outflow. Given the graph of overland flow, then the amount of infiltration on the basin can be readily derived through the storage-equation. Intensive researches on infiltration are being made by the United States Department of Agriculture, and this work is supplemented by the cooperation of a special advisory committee from the Section of Hydrology of the American Geophysical Union. The agricultural colleges also have made experimental determination of infiltration-rates and they have performed the much-needed work of analysis and interpretation of the data.

The following phenomena of infiltration seem to be substantiated: (1) Surface-runoff occurs when the rain-intensity or rate of melting snow exceeds the existing infiltration-capacity of the soil; (2) there is a pronounced difference in infiltration-capacities with soils of different type and texture; (3) with continuous excess rain, of uniform intensity, on normal ground-surface, the infiltration-rates will be relatively high at the beginning of the storm, and the infiltration-rates will approach a constant as the storm continues--this may be called the infiltration time-profile; (4) the soil infiltration-capacity at the beginning of a storm is relatively high or low, depending upon the initial moisture-content of the soil; (5) the initial soil moisture-content reflects the antecedent weather-history--the amount of rain and the intervening evaporation-period; (6) the average storm infiltration-rates follow a very definite cycle of seasonal variation throughout the year.

In principle and methodology, we have just reached the important position where we can begin to accurately estimate infiltration and, therefore, the point where we can definitely forecast flood-runoff. There is need for (a) more determinations of average infiltration-rates on natural basins and (b) derivation or forecasting of initial soil moisture-content by means of antecedent weather-history of the basin.

Flood-wave velocity or time of transit on a river-system is a useful and important element in flood-forecasting. The fundamentals of the hydraulics of flood-waves have been known since the time of Darcy and Bazin and James Seddon. The "daily river-stages" forecasts for navigation on the Ohio and Mississippi rivers have been made for many years.

Recently studies or procedures have been made for timing and routing of floods on a river-system. This time-element of flood-peak transit seems to offer an opportunity for a flood-forecasting period. It may be that it designates the limiting or maximum time in advance when flood-stages may be forecast. For example: On the basin of the Vermillion River (1200 sq. mi. D. A.) above Danville, Illinois, the crest of the flood at Danville follows 22 hours after the center of precipitation of the storm. By means of the unit-graph or distribution-graph, together with a knowledge of the soil infiltration-capacity at the time, it is possible to forecast 20 hours in advance what the river-stage at Danville will be. If a general storm were taking place over the entire valley of the Wabash River, the other tributaries similar to the Vermillion Basin would be included in the forecast-data. All of the tributary runoff-graphs, combined on a flood-routing diagram for the Wabash River System, would at once give a forecast of the flood-stage that would occur at Vincennes, Indiana, two days later. If the general storm continues, later forecasts will give, 48 hours in advance, the expected higher stages.

Runoff, due to melting snow without rain, in certain localities, is forecast several weeks in advance.

Potential-flood forecasts can and should be estimated for a river-system long in advance. For example: There may exist a saturated soil on the basin combined with high river-stages. The beginning of any storm then is a signal of danger. The flood-stages should be computed in advance, assuming the possibility of the occurrence of a major storm under these potential-flood conditions.

In the writer's opinion, we are now in a position to forecast floods and flood-stages. The antecedent forecast-time possible is the time-lag between the middle of the storm-occurrence and the peak of the corresponding hydrograph of runoff (less one hour for mechanized computations).

The hydrologist can only begin his forecasting after precipitation reaches the ground. Any flood-forecasting in advance of that time awaits progress in the realms of the meteorologist.

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DISCUSSION OF MR. SHERMAN'S PAPER

Waldo E. Smith

Inasmuch as the writer is associated with one of the projects on which the forecast of stream-stages is important, he is in a position to appreciate Mr. Sherman's remarks on the difficulty of the making of forecasts as compared with the matter of establishing the stage-frequency for various intervals from past records. The recent advances along the line of forecasts have gone forward so rapidly that at the present time the matter of technique of establishing a forecast at a given point is perhaps carried farther than the ability and reliability of securing the data on which the technique is based. During the progress of a storm, speaking specifically of conditions on watersheds on which forecasts must be made largely from precipitation-data, there is a limit to the amount of physical data that may be accumulated in a period short enough that the forecast will still be a forecast. There is the further difficulty often overlooked that in times of flood-emergencies the usual means for gathering the essential data are likely to fail. It has been characteristic of floods of major magnitude that telephonic and telegraphic communications are no longer serviceable. It would thus appear that hydrologists and others concerned with the matter of flood-control and forecasting should look to more reliable means for the gathering of data at critical times. Failure of communications made it impossible for the Weather Bureau to secure data to forecast properly at Pittsburgh during the flood of March 1936. Because of this the Weather Bureau was severely criticized. It is not only sufficient that we be cognizant of these shortcomings, but it is imperative that steps be taken to rectify the situation. Our technique of forecasting is worthless if we are unable to secure the basic data on which forecasts must be based. We must now improve our means for collecting data quickly.

Initial developments have been made along this line in California, the Tennessee Valley, and elsewhere to secure flood-stages direct from gaging-stations by means of radio with automatic sending equipment at the gaging-station. Many difficulties are involved which probably can be eliminated as the instruments are developed, but before we have adequate and dependable means for collecting the necessary data for flood-forecasts this work must be done.

The author mentioned also the matter of flood-forecasting through weather-forecasts. As the present studies in the field of air-mass analysis become perfected it is to be hoped that this can be done, but it seems hardly advisable in most instances now to operate flood-control works or forecast flood-crests on the basis of forecast precipitation.

The author has stressed the forecasting of flood-crests, but in many instances it is impossible to establish flood-crests because of continuing rainfall. This is especially true on smaller watersheds through recent performances in the Ohio Valley in the vicinity of Cincinnati (the floods of January 1937 and of April 1939) which have indicated the great importance of small streams close to the valley proper in increasing flood-stages very markedly by rainfall occurring within a short period before the increase in stage is noted. However, even on quite small watersheds the rise by precipitation within a 12-hour period is usually not noticeable in great measure until the end of the succeeding 12-hour period. It is thus possible to establish reasonably accurate forecasts for moderate-sized watershed for 12-hour periods in times of continuing rainfall. Beyond that time for an additional 12-hour period allowance can be made for anticipated

or forecast precipitation usually without great sacrifice in accuracy. It is here that weather-forecasts can ultimately play an important part in forecasting.

Muskingum Watershed Conservancy District,
New Philadelphia, Ohio

THE MEASUREMENT AND COMPUTATION OF FLOOD-DISCHARGE

Carl G. Paulsen

(Published with the approval of the Director, U. S. Geological Survey)

The Geological Survey has been engaged for more than 50 years in measuring and publishing the discharge of streams of the United States. Measured discharges have ranged in quantity from a small fraction of a second-foot measured volumetrically to more than 2,000,000 second-feet measured by use of the current-meter equipment recently developed by the Survey and described by the writer in the April 1938 issue of Civil Engineering. In this work, systematic and generally complete records of discharge are being obtained at about 3700 gaging-stations maintained and operated by the United States Geological Survey. A typical structure at which records of river-stages are obtained is shown in Figure 1. A discharge-record at a gaging-station is usually derived from a record of stage by means of a curve or table showing the stage-discharge relation as determined by measurements of discharge distributed over the range of stage.

The United States Geological Survey determines not only the distribution of runoff through the year, but also the noteworthy and record-breaking extremes of discharge. Measurements of flood-flows require special methods which are not as well developed and understood as are the methods used in measurements at ordinary stages. Many streams rise and fall so rapidly that the

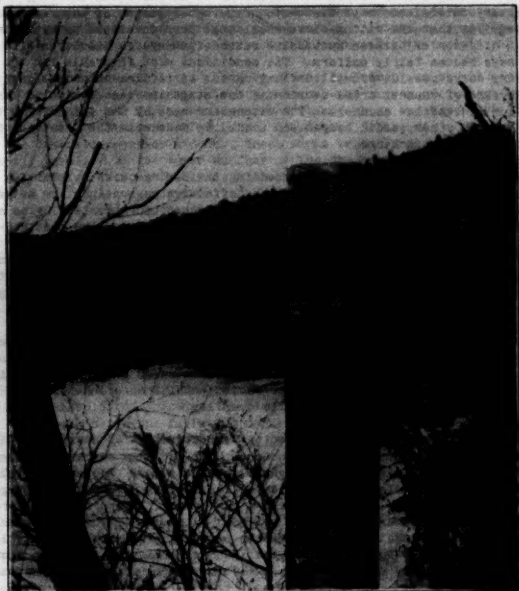


FIG. 1—STRUCTURE AT WHICH RECORDS OF STAGES ARE OBTAINED,
POTOMAC RIVER AT PAWPAW, WEST VIRGINIA

time is insufficient for current-meter measurements at high stages. Means of transportation and communication may fail during floods so that engineers cannot reach those places where measurements of flood-flows are needed, or the value of an opportune arrival by the engineer at the time of crest-stage may be nullified by the presence of floating debris or by the destruction of the bridge or cableway from which measurements are made usually thus making impracticable, if not impossible, the measurement of discharge by a current-meter. Consequently, in many instances it may be necessary to determine flood-flows by means of surveys and information obtained after the flood has passed. As the accuracy of such determinations will depend largely on the accuracy of the surveys and the extent of the information that can be obtained, the field-work must be done at the earliest practicable moment.

A thorough reconnaissance of the stream or streams in the flood-area is made to find the points at which determinations of the flow are possible. As high-water marks are obliterated very quickly, such marks as are available should be fixed by surveys or referenced by markers until surveys can be made. Each determination of flood-discharge is a distinct hydraulic problem requiring for its solution a thorough knowledge of the principles involved, and sound judgment in the selection of suitable sites and of the methods to be used. Careful and logical analyses of the situation and of the information obtainable will generally produce consistent and satisfactory results, even where conditions may at first appear to be unfavorable. It is generally desirable to determine the maximum discharge by two or more different methods, or, failing in that, by means of two separate and independent sets of observations. Careful notes containing complete details of field-data and observations, together with good photographs, are necessary.

The application of the methods commonly used for determining flood-discharges will be described under appropriate headings.

Extension of rating-curve

The satisfactory determination of flood-discharge by extension of the rating-curve at a gaging-station requires that the rating-curve shall have been developed by actual measurements to a stage where the differences between successive rates of change in discharge with respect to change in stage have become fairly uniform. The conditions most favorable for the accurate extension of a rating-curve consist of well-defined rapids or riffles below the gage at all stages and a uniform increase of channel cross-section as the stage increases, with no abrupt changes in area or addition of overflow channels. The extensions made by the following methods should be checked against each other, and a comparison should be made with the results obtained by other methods of determining the discharge.

(1) Extension on logarithmic paper--In extending the rating-curve by plotting on logarithmic paper, the measured discharges are plotted against "effective gage-height" or height above the stage of zero-flow. The stage of zero-flow may be determined approximately by an examination of the lower part of the rating-curve, or by cut-and-try methods to find the constant which must be applied to the observed gage-heights to cause the higher discharge-measurements to tend to plot in a straight line or a very flat curve. Under these conditions with an appropriate knowledge of the influential factors the line may be extended to higher stages with satisfactory results for channels not subject to overflow.

(2) Extension by $d-Q'$ --In the $d-Q'$ method of extension, the mean depth, d , is plotted on logarithmic paper against the average discharge per foot of width, Q' . The line through the plotted points may be extended to the value of d corresponding to the cross-section of the channel at the crest-stage. This method appears to be reliable under favorable conditions but lacks extensive verification for long extensions under varied conditions of channel, and is not well adapted to irregular channels or those subject to overflow.

(3) Extension by studies of areas and velocity--In extensions of areas and velocities, the area of cross-section is plotted against gage-height to define an area-curve. This area-curve may be accurately defined by surveys to the highest desired stage. The average velocity in the section as determined for each discharge-measurement is similarly plotted against gage-height. For channels not subject to overflow, the velocity-curve generally approaches a straight line at high stages and reasonably good extensions may be made by the use of judgment and experience. The discharge for the flood-stage is obtained as the product of the area and velocity from the extension of those two curves. In the application of this method consideration should be given to the existence of satisfactory relationship between the stages at the gage and stages at the measuring section.

(4) Extension of discharge as a function of $\sqrt{Vd}$ --In the extension of the discharge-curve

as a function of $A\sqrt{d}$, the product of the area and the square root of the mean depth, $A\sqrt{d}$, is plotted against measured discharge on rectangular cross-section paper, the values of A and $\sqrt{d}$ having been determined from the area of the cross-section. A line through the plotted points may be extended to the value of $A\sqrt{d}$ for the desired stage. This method is applicable if the extension above actual discharge-measurements is not too great, and if the channel-shape at flood-stages is similar to that at which discharge-measurements were made.

Slope-area method

The slope-area method requires the use of a formula, generally in the basic form of $V = C\sqrt{RS}$, in which the factors R and S are evaluated from measurements in the field after the flood has subsided. The coefficient C , which includes the effect of the roughness of the channel, may be evaluated by various formulas, the Manning formula generally being considered preferable. [The application of the slope-area method is described in Geological Survey Water-Supply Paper 816, pp. 11-15.]

(1) Selection of reach--Care in choosing the reach of river-channel for use in a determination of discharge by the slope-area method does much to improve the accuracy of the results by eliminating or minimizing the effects of unfavorable conditions. The following factors are among those which should be considered: (a) Alignment of channel--should be as nearly straight as can be obtained; (b) length of reach--not too long, as conditions of uniformity generally decrease as the length increases, but should be of sufficient length for satisfactory determination of the fall within the reach; (c) uniformity of cross-section and slope is desirable, and reaches should be avoided in which the area of cross-section of channel increases downstream or in which there are adverse bottom slopes--channels having overflow areas should be avoided, if possible; (d) the banks of the channel should be free from trees, brush, and other obstructions; (e) the bed and banks of the channel should be stable and not subject to erosion or deposition during the flood; (f) the high-water marks should be sufficient in number and of good definition for the accurate determination of the crest-stage; (g) presence and movement of debris--the effect of the movement of large quantities of debris is minimized by selecting a reach in which the channel is relatively narrow and decreasing in area and through which the velocity is increasing.

(2) Survey--At each site where the discharge is to be determined by the slope-area method, a survey is made by stadia, plane-table, or other means, the survey including the high-water marks on each bank through and for a considerable distance above and below the slope-reach. A profile of the high-water points so obtained may be plotted in the field and a study made of the uniformity of the indicated surface-slopes. These marks probably show the crest-stage or define a line very nearly parallel to the water-surface of the crest-stage. Two or more cross-sections are surveyed, so situated that hydraulic conditions between them are as nearly uniform or constant, as shown by uniform slopes on both banks, as can be obtained. If the cross-sections vary in area, it is essential that the change in area be small or at least that the change be gradual. On streams having beds subject to scour during floods and later filling with fine materials, the position of the bed at the time of the maximum discharge should be determined as carefully as possible. Streams with very steep slopes may have satisfactory reaches above weirs and dams which have filled to the crest and thereafter acted as stabilizers of the channel. High-water marks on the ground where wave-action and surge are at a minimum are generally preferred to marks in bushes and trees. Notes are made respecting the character of the bed and banks of the channels, and any other conditions which may be pertinent to the particular measurement. Photographs are taken to show channel-condition and to help in the selection of the coefficient n .

(3) Office procedure--The data obtained by the surveys are plotted and from these data-sheets tabulations are made of the essential factors entering into the computations of the flood-discharge. Partial examples of procedure as given in Geological Survey Water-Supply Papers 773-E, 798, 799, 800, and 816 contain the following data: (a) Map or sketch to scale, showing the channels and the positions of the high-water marks; (b) longitudinal profile showing positions of the high-water marks from which the water-surface slope of the stream is to be determined; (c) cross-sections of the channels; (d) computations of the area and hydraulic radius of each channel into which a reach may have been subdivided.

It is customary to divide a reach into several channels if the relative conveyance-capacities of the different parts of the cross-section differ because of different values of the hydraulic radius and the coefficient of roughness. In determining the wetted perimeter of a channel in a subdivided reach, it is customary to neglect that portion which is common to the adjacent channel or channels, unless there is a well-defined line of demarcation between the channels such as might be caused by a dense line of trees or division of the channel. Profiles of high-water marks and sections of slope-area reach used in computations of flood-discharge on the Concho River near San Angelo, Texas, are shown in Figure 2.

MAJOR TEXAS FLOODS OF 1936

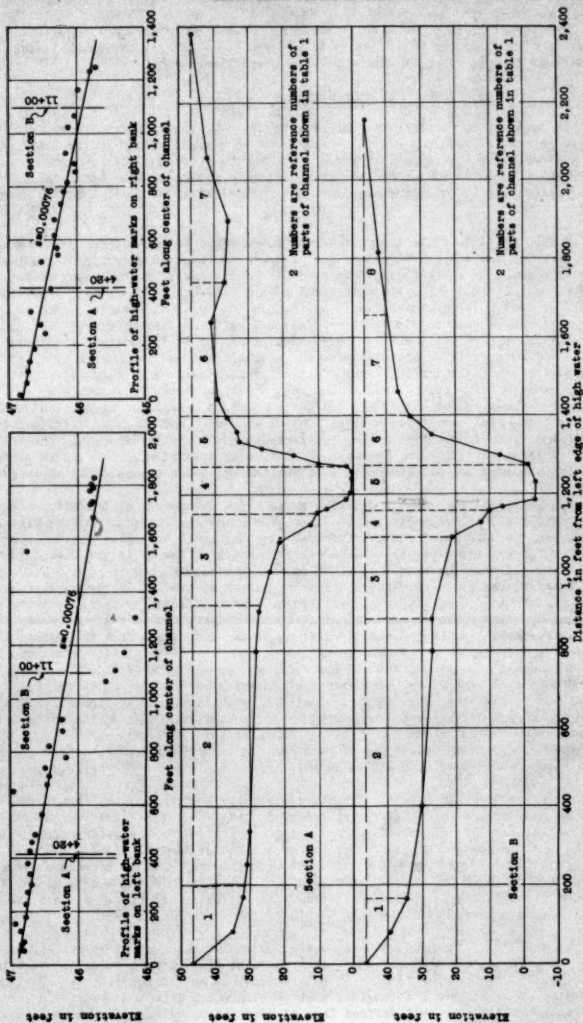


FIG. 2—PROFILES OF HIGH-WATER MARKS AND SECTIONS OF SLOPE-AREA REACH ON CONCHO RIVER NEAR SAN ANGELO, TEXAS

(4) Assumptions and computations--A value of the coefficient of roughness, n , is selected corresponding to the condition of the channel. The values of n may differ for the different parts of the cross-section into which the channel may be divided. Pertinent information on the value of n for streams flowing less than 15,000 second-feet may be found in a report by C. E. Ramser, "Flow of water in drainage-channels, the results of experiments to determine the roughness coefficient n in Kutter's formula" [U. S. Dept. Agric. Tech. Bull. 129, November 1929]. If the flow in any reach is not uniform, it is necessary to consider the velocity-head and to adjust the slope s to a value representing the energy-grade line. If the velocity at a downstream section is less than that at an upstream section and there is a transformation of kinetic energy into potential energy, it is customary to assume the actual recovery to be 50 per cent of the theoretical recovery [J. R. Freeman, "Regulation of the Great Lakes," p. 303, 1926; and J. C. Stevens, discussion of "Varied flow in open channels of adverse slope," Trans. Amer. Soc. Civ. Eng., v. 102, p. 669, 1937]. Variations in this percentage may be made if the conditions warrant. This correction is simple and easily made if the flow is confined to one channel. Where a reach is divided into two or more channels with different values of n and different hydraulic radii, the weighted velocity-head for the section is determined by an adaptation of equations given by M. P. O'Brien and G. H. Hickox in "Applied fluid mechanics," page 271. See also United States Geological Survey Water-Supply Paper 816, page 15. An example of a slope-area discharge-determination of 580,000 second-feet, giving in detail all assumptions and computations, is presented in Geological Survey Water-Supply Paper 796-G.

Contracted-opening method

The contracted-opening method involves the computation of the discharge from the measured drop in water-surface in a short contracted section, such as the opening between bridge-abutments. Under those conditions the discharge may be computed by the formula $Q = k A \sqrt{2g} [H + (V^2/2g) - h_f]$, where Q = discharge in second-feet, k = coefficient of contraction, to be applied if the water moves around a sharp corner in entering the contracted section, A = area, in square feet, of the most contracted section, H = surface drop, in feet, at the entrance to the contracted section, V = velocity of approach, in feet per second, and h_f = head loss, in feet, due to friction.

An application of the contracted-opening method showing computations for the determination of discharge of Dry Creek near San Angelo, Texas, for the flood of September 17, 1936, may be found in Geological Survey Water-Supply Paper 816, page 17.

(1) Selection of the contracted opening--Contracted openings suitable for use in the computation of discharge are generally those between bridge-abutments. In the selection of a contracted opening the following factors are considered: Alignment of the opening with the channel; shape and condition of the approach-channel; position and definition of the most contracted section in the opening; length of the contracted section; stability of the opening during the flood; quality and quantity of the high-water marks; amount of drop in the opening; probable accuracy of the definition of the draw-down curve.

(2) Survey--At each site an instrumental survey is made of the opening, structures, and high-water marks on each bank for a considerable distance above and below the opening to define the average slope above the drop, the draw-down curve, the lowest part of the trough in the contracted section, the standing wave, and the slope below the drop. Cross-sections are measured in the approach-channel, the most contracted part of opening, and such other places as may be significant. High-water marks are selected with the same care as described for the slope-area method. Notes are made of conditions at and near the opening and at other points which might be pertinent to the computation; also of the entrance-conditions, especially at bridge-openings, with reference to the selection of the coefficient k . Photographs are obtained of the opening, the approach-channel, and the conditions below the contracted section. The map, profiles of high-water marks, and sections used in computation of flood-discharge of Dry Creek near San Angelo, Texas, are shown in Figure 3.

(3) Office procedure--The data obtained in the field are plotted and from those data, maps, profiles, and computation sheets are prepared as follows: (a) Map or sketch to scale, showing layout of structures, channels, and high-water marks; (b) longitudinal profile showing the high-water marks from which the position of the water-surface is determined and the position of the contracted opening is shown (this profile is essential for the development of the draw-down curve); (c) cross-sections of the channel of approach and contracted section; (d) sheets with the computation of the area and hydraulic radius of the cross-section of each individual channel into which the total area of the channel in the reach may have been subdivided.

(4) Assumptions and computations--The selection of the coefficient of contraction k to be

applied if the water moves around sharp corners in entering the contracted section is largely a matter of judgment and experience. It is generally assumed that the coefficient K is not less than 0.90 or 0.95 [1. E. Houk, "Calculation of flow in open channels," Miami Conservancy Dis-

MAJOR TEXAS FLOODS OF 1935

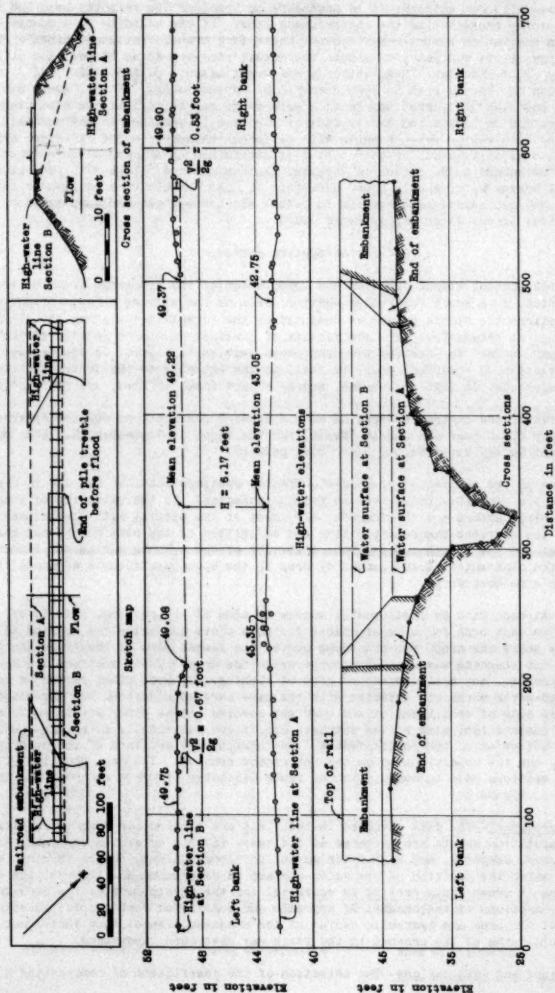


FIG. 3—MAP, PROFILES OF HIGH-WATER MARKS, AND SECTIONS FOR CONTRACTED-OPENING MEASUREMENT ON DRY CREEK NEAR SAN ANGELO, TEXAS

trict Tech. Report, Part 4, p. 264, 1918]. If the transition from the approach-channel to the contracted section is gradual, with no abrupt projections or sharp corners, the coefficient k may be nearly unity. The velocity-head may be determined from cross-sections of the approach-channel. The head-loss due to friction h_f may be computed by first assuming an approximate value of h_f and subtracting that value from the total head, then computing the friction-loss for the length of the contracted section [idem, p. 56]. If the computed value of h_f differs materially from the assumed value, a second computation may be made.

Flow over dam

The method of computing the flow over a dam involves also the determination of the flow over or through the appurtenant structures.

(1) Selection of dam--On some rivers, dams are many miles apart and little choice is offered, but, so far as practicable, the following factors should be considered in the selection of the dam: Angle of dam with channel; alignment of crest of dam; approach and get-away conditions; velocity of approach; stability of crest of dam during flood; selection of representative coefficients for the discharge over the dam and through sluices or wasteways; extent of submergence of the dam by backwater; uniformity of cross-section of crest; flow over bulkheads, past the ends of the dam, through gates, wheels, flumes, and other appurtenant structures.

(2) Survey--A survey by stadia, plane-table, or other means is made at the dam as a basis for a map showing the dam and all the appurtenant structures such as bulkheads, canals, gates, intakes, and wasteways of all kinds. The high-water marks, carefully selected as previously discussed under the "slope-area method," are sought, studied, and shown on the map on both sides of the river for a considerable distance above and below the dam. In many instances the high-water marks above the dam may be used not only to determine the static head on the dam but also the slope of the water-surface in the approach-channel from which the velocity of approach may be computed. The high-water marks below the dam may be used to determine the amount of submergence of the dam and the general downstream conditions. The length, elevation, and cross-section of any structure over which the water flowed, and the sizes and positions of all gates, openings, orifices, and sluices for which the discharge is to be computed are also determined by the survey. Similar information is obtained relative to the size, shape, slope, and position of channels through which water may have bypassed the dam. One or more cross-sections are surveyed above the dam for the determination of the velocity of approach. Weirs and dams in streams of very steep slopes may become filled to the crest with sand, gravel, and other material, and in some instances may lose their identity as weirs and act merely to stabilize the channel, with a velocity of approach greater than the critical velocity for the weir or dam. Under those conditions the usual methods of computing the flow over a dam may not be applicable. In some instances this condition of channel has been found suitable for use in the slope-area method.

Notes are made relative to the condition and details of the structures in connection with the selection of coefficients for use in formulas for the computation of the flow. It is necessary that the shape of the crest of the dam, especially the upstream part of the crest, should be accurately determined in order that the proper value of the coefficient C may be selected. The possibility that the nappe may jump clear of the structure so that the dam functions as a sharp-crested weir should be investigated. If the shape and height of the crest is uniform throughout the entire length, a discharge-measurement of the flow over the dam at a fairly high stage will make possible a determination of the coefficient C for that stage, and the coefficient thus determined can be used as a guide in selecting the value of C for higher stages.

It is necessary to ascertain if there were flashboards on the dam at any time during the flood, and if so, their condition during and immediately after the flood. It is also necessary to obtain information regarding the positions, dimensions, and heights of any old dams, cofferdams, or other structures which may be in place immediately above the dam, as such structures may have a decided effect on the flow over the dam. Photographs should be taken of all the structures and of the channels above and below the dam.

(3) Office procedure--The data obtained in the field are plotted and from these data, maps, profiles, and computation-sheets are prepared as follows: (a) Map or sketch to scale, showing layout of structure and channels with the relative positions of high-water marks; (b) longitudinal profile showing the pertinent structures and the high-water marks from which the flood-profile is to be determined; (c) cross-sections of the channels and of the structures through or over which the water flowed; (d) computations of the area and the hydraulic radius of each section or channel which may be used in the determination of flow.

(4) Assumptions and computations--For a dam having a uniform section similar in shape to the section of a dam for which the rating- or discharge-coefficients are known, it is generally possible to convert records of stage into records of discharge with a good degree of accuracy by satisfying the general formula

$$Q = CLH^{3/2} \quad (1)$$

In this formula Q is the discharge in second-feet, C is the coefficient for the dam, L is the length of the crest in feet, and H is the total head in feet. Since the total effective head is the sum of the pressure-head h_p and the effective velocity-head $h_v \sin \theta$, where θ is the angle between the crest of the dam and the direction of the current, the formulas

$$h_v = \alpha (V^2/2g) \sin \theta \quad (2)$$

$$H = h_p + \alpha (V^2/2g) \sin \theta \quad (3)$$

may be written, where V is the average velocity in the approach-channel section and α is a correction-factor due to unequal distribution of velocity. The value of α in an unobstructed stream has an approximate range of 1.1 to 1.4, while back of a dam or other obstruction it may be as much as 2.0 or more.

Where necessary, allowance is made for submergence of the crest by backwater. If the submergence of sharp-crested weirs is less than about 15 per cent of the total head, the discharge is not sensibly affected. Broad-crested and round-crested weirs are probably not sensibly affected by submergence up to about two-thirds of the total head. Material assistance in the selection of coefficients for dams and for submerged weirs may be obtained from the results of experiments published in Geological Survey Water-Supply Paper 200, "Weir experiments, coefficients, and formulas."

The flow over highway- and railroad-embankments is considered as analogous to the flow over dams, and values of the coefficient C to be used under those conditions may be selected from experimental data in "Flow of water over railway- and highway-embankments" by D. L. Yarnell and F. A. Nagler published in Public Roads, April 1930.

The flow through sluice gates, flumes, penstocks, wheels, and other appurtenant structures is computed by formulas which are discussed in numerous engineering publications.

Other methods

Critical-depth method--The critical-depth method is applicable where there is available an exceptionally good natural or artificial control over which it is reasonably certain that flow has taken place at critical depths. Points of critical-depth control may occur at or near changes in bottom-slope, upstream from which the bottom-slope is less than is necessary to maintain uniform flow at the critical depth, and downstream from which the bottom-slope is greater than is necessary to maintain such flow.

Surveys of sites for the determination of flood-flows by the critical-depth method are similar to those for slope-area reaches with special attention to the cross-section of the control at which it is assumed that flow had taken place at critical depths.

Data obtained in the field are plotted and data-sheets are prepared in a manner similar to those for use in the slope-area method.

Discharges are computed by use of equations adapted from those given by King in "Handbook of hydraulics" and by O'Brien and Hickox in "Applied fluid mechanics." [See also R. A. Dodge and M. J. Thompson, "Fluid mechanics," pp. 241-254, 1937.]

This method should be used with caution as it is difficult to be certain that flow occurred at critical depth through the control-section selected in the field.

Timing of flood-drift--The velocity of drift is occasionally observed in determining the velocity if a current-meter is not available or its use is impracticable. Velocities are observed in as many different parts of the channel as possible by timing the travel of drift over a known distance. Drift which is largely submerged should be selected for timing. The average velocity is computed from the observed velocities by the use of suitable coefficients. The area of cross-section, being either known or measured after the flood, the discharge is determined as the product of the area of the section and the average velocity.

Computation by formulas--In the absence of actual records, flood-flows may be computed by the use of various formulas and methods involving observed precipitation and correlations of rainfall and runoff. The development, use, and relative merits of the various formulas and methods have been described and discussed in textbooks and technical publications and are too numerous and complex for review and discussion in this paper. The computation of discharge by rainfall-runoff studies is presented in detail in Geological Survey Water-Supply Paper 844. The technique and procedure of estimating floods are comprehensively reviewed, flood-statistics for streams where long-time records are available are compiled in form for ready reference, and a bibliography relating to flood-flow and intense rainfall are contained in Geological Survey Water-Supply Paper 771, "Floods in the United States--magnitude and frequency." The results of investigations of relations between annual and monthly precipitation, temperature, evaporation, transpiration, direct surface-runoff, ground-water runoff, and infiltration as a basis for the quantitative analysis of the hydrologic cycle and of trends and changes therein are presented in Geological Survey Water-Supply Paper 772, "Studies of relations of rainfall and runoff in the United States." Investigations of relations between precipitation and direct surface-runoff and a list of references to articles and discussions of the relations between rainfall and runoff are also contained in the last-mentioned publication.

Publications

The United States Geological Survey has published during the past four years or has in preparation for publication the following water-supply papers presenting inventories of the precipitation and discussions of the major factors involved in the floods, records of discharge during the flood-periods, and historical records of previous floods from which hydrologists, engineers, and others may draw basic information.

Water-Supply Paper	Title
773-E	The New York State flood of July 1935
796-B	Flood on Republican and Kansas rivers, May and June, 1935
796-C	Flood in La Cañada Valley, California, January 1, 1934
796-G	Major Texas floods of 1935
798	The floods of March 1936, New England rivers
799	The floods of March 1936, Hudson River to Susquehanna River Region
800	The floods of March 1936, Potomac, James, and upper Ohio rivers
816	Major Texas floods of 1936
836-A	Stages and flood-discharges of the Connecticut River at Hartford, Connecticut
838	Floods of Ohio and Mississippi rivers, January-February, 1937
842	Flood in Canadian and Pecos River basins, New Mexico, 1937
843	Floods of December 1937, northern California
844	Floods of March 1938, southern California
...	Flood of August 1935 in the Muskingum River Basin
...	The hurricane floods of September 1938
...	Floods in the Colorado River Basin, Texas, 1938

At many gaging-stations the peak-flows of the floods described in these publications greatly exceeded the highest flows in which current-meter measurements had been made and it was necessary to determine the maximum discharges by one or more of the methods described herein. The United States Geological Survey has made many determinations of flow by these various methods, ranging from about one second-foot to about 600,000 second-feet and in 50 years of measuring the flow of streams has acquired a broad experience and background in the determination of flood-flows under various field-conditions. The methods commonly used for determining flood-flows are those given in textbooks and in many instances the involved published coefficients have been deduced from experiments in the laboratory within a narrow range of conditions. The United States Geological Survey has had many opportunities for verifying the methods and the checking or modifying the coefficients under conditions of great floods and for ranges of conditions far beyond those possible to obtain in a laboratory. Such verifications, checkings, and modifications have increased confidence in the reliability of the methods. It is difficult to obtain reliable measurements by which to check individual determinations of flood-flow, but the cumulative weight of the verifications obtained by comparisons of the results by the different methods has left little doubt as to the general value and reliability of the methods. The following examples of the verification of the results obtained by the use of different methods have been taken from the records and files of the Boston District Office of the United States Geological Survey. Many more similar examples may be found in the records and files of other district offices.

Birch Brook near Williamstown, Massachusetts

Example A--0.97 second-foot over sharp-crested V-notch control; 1.08 second-feet by critical-depth method

Example B--67 second-feet over sharp-crested V-notch control; 74 second-feet by slope-area method; 74 second-feet by critical-depth method

Housatonic River at Dalton, Massachusetts

6290 second-feet flow over Byron Weston Company Dam; 6550 second-feet flow over Pioneer Mill Dam

Blackwater River near Webster, New Hampshire

Example A--6580 second-feet by current-meter measurement; 6750 second-feet by slope-area method; 6790 by the critical-depth method applied to a control-section about 150 feet below the gaging-station

Example B--9140 second-feet by the critical-depth method applied to a control-section about 150 feet below the gaging-station; 9210 second-feet by the critical-depth method applied to a control-section about 0.3 mile below the gaging-station; 9900 second-feet by slope-area method

North Nashua River near Leominster, Massachusetts

9640 second-feet by slope-area method (fair reach only); 11,000 second-feet computed flow over dam (poor condition)

Hill River at East Clarendon, Vermont

19,500 second-feet by slope-area method; 18,100 second-feet computed flow over dam

Millers River at Erving, Massachusetts

19,700 second-feet computed flow over dam; 19,800 second-feet by slope-area method; 19,300 second-feet by contracted opening method

Contoocook River at Penacook, New Hampshire

39,900 second-feet by current-meter measurement; 40,700 second-feet from extension by area-velocity study of rating-curve defined by current-meter measurements below 16,000 second-feet

38,200 second-feet by contracted-opening method (3 miles upstream from gaging-station) at stage 0.35 foot above current-meter measurement; 42,400 second-feet from extension of rating by area-velocity study

Deerfield River at Charlemont, Massachusetts

56,000 second-feet by contracted-opening method; 56,300 second-feet by slope-area method;

56,000 second-feet from rating-curve defined by current-meter measurements below 10,000 second-feet and previously extended to and above 32,000 second-feet on the basis of the average of previous determinations of flood-flows by slope-area and contracted-opening methods

Merrimack River at Franklin Junction, New Hampshire

59,900 second-feet by slope-area method; 57,700 second-feet, combined flow computed over dam of 54,500 second-feet and an intervening inflow of 3200 second-feet determined from stage-discharge relation; and 58,700 second-feet from extension of rating-curve defined below 30,000 second-feet and previously extended to 83,000 second-feet on basis of velocity-area study at control-section

Merrimack River at Lowell, Massachusetts

206,000 second-feet by slope-area method; 173,000 second-feet from rating-curve defined below 147,000 second-feet by current-meter measurements and extended to peak-stage

Connecticut River below Hartford, Connecticut

305,000 second-feet by slope-area method; 290,000 second-feet maximum discharge and 270,000 second-feet discharge at peak-stage, determined from measured inflow from 98.4 per cent of the drainage-area adjusted for storage and inflow

In many drainage-basins there were several gaging-stations along the main stream and tributaries. The consistency of the results obtained by comparisons of the instantaneous discharges and the total runoff at these gaging-stations attests to the reliability of the higher-water ratings at these stations, many of which had been based in part on determinations of flood-flows by the methods discussed in this paper.

Every effort should be made to measure the velocity of flood-flows by means of a current-meter. If this is impossible or impracticable, good field-data properly analyzed have been found to yield satisfactory results. A more extensive use of auxiliary methods for determinations of flood-flows should be encouraged in order to accomplish the following purposes:

- (1) Improve the probable accuracy of flood-flow determinations.
- (2) Improve the ratings at high stages with the consequent improvement of flood-records. Many ratings are now necessarily extended far beyond the discharge of the highest current-meter measurement.

- (3) Training of personnel in the study of practical hydraulic and hydrologic problems.
- (4) Systematic test of the applicability of existing equations and methods for determining flood-flows under extreme conditions of steep slopes, erodible beds, compound channels, and other conditions.
- (5) Foster systematic investigation of present methods and the development of new methods and procedures.
- (6) Relief from the criticisms which have been made or may be made because of the necessity for determining flood-flows by various little-used methods if actual measurements by current-meter at peak are impracticable.

U. S. Geological Survey,
Washington, D. C.

RECENT DEVELOPMENTS IN FLOOD-FORECASTING

Merrill Bernard

From the prophecies of the Ancients to the crystal-gazing of the Moderns, man's urge to know his fate has been in opposition to the wisdom of a Providence that mercifully cloaks the future and reduces the outlook largely to speculation; and flood-forecasting, in the general sense, is an example of this characteristically human effort to foretell events. The purpose of this discussion is to consider modern man's attempt to organize his knowledge of floods in order to foresee (1) the extreme experience to which his flood-control works will be subjected, (2) the number and magnitude of the lesser floods that will probably occur, and (3) the approach of the individual flood.

A flood is that temporary unbalance in Nature that results when more water is applied to the land in the form of precipitation than can be absorbed by the land itself and its vegetation, or retained in natural reservoirs and man-made works for providing storage. The localized effect is the rapid rise of the water to and above the in-bank capacity of the channel-system, with the accompanying inundation in many cases of fertile and highly developed valley-areas.

In Table 1 are classified and compared three types of flood-forecasting. The principal distinction lies between those taken as the basis of design for flood-control works and that intended to facilitate the evacuation of populations and the removal of property from the path of an oncoming flood.

Table 1--Flood-forecasting classified

Class	Purpose	Basic considerations	Terms in which forecast is expressed	Essential data	Basic procedure
Maximum flood	To establish the capacity-limits of control-works	Social	Magnitude Duration	All available meteorologic and hydrologic data for the region	Analytical and synthetic
Probable flood	To evaluate the accepted tolerances in the design of control-works	Economic	Magnitude Duration Frequency	All available meteorologic and hydrologic data for the region	Analytical and statistical
Individual flood	To prevent loss of life and reduce damage to that to immovable property	Social and Economic	Magnitude Duration Expected hour of occurrence	Current meteorologic data for the region and hydrologic data for the basin promptly assembled	Analytical

The forecast of the "maximum flood" is essential in situations where, principally for social and psychological reasons, the flood must be completely controlled; that is, where storage plus spillway (or flood-way) capacity must be adequate to accommodate the greatest possible flood the region is capable of producing. Such a forecast can be expressed only in terms of magnitude and duration. No significant periodicity can be assigned to this limiting or "maximum flood."

The forecast of the "probable flood" becomes the criterion of design for the less important flood-control works usually involving no hazard to life and whose justification must be largely economic. This class of forecast does not attempt to fix the sequence or the actual dates of the floods which can be expected to occur within the economic life of the structure, but states simply that certain flood-magnitudes and durations will be reached or exceeded on the average of once in X years.

The forecast of the "individual flood" must anticipate from the immediately determinable causal factors the results of their subsequent combinations. To be most effective it must express the expected flood in terms of magnitude, duration, and the expected hour of occurrence.

Forecasting the maximum flood--It will be well, first, to acknowledge the limitations which hedge about this class of forecasting. Our records of storm and flood are short and our knowledge of meteorologic and hydrologic relationships are elementary. We have paid dearly for these inadequacies, not so much in the failure of the works we have built, but in the admittedly extravagant factors of safety which have characterized design in the past.

Our records of stream-flow are shorter, less extensive, and not so dependably subject to interpolation as our records of precipitation. This accounts largely for recent trends to storm-rainfall as the basis for flood-estimation, for the meteorological background of the storm has been found to add materially to the interpretability of our shorter records of hydrologic data.

We have then to consider: (1) The storm; (2) the rainfall resulting; (3) the conditions of surface and cover on the basin which will prevent a certain portion of the rainfall from contributing to the flood; (4) the arrangement of the stream-pattern and the physiography of the basin which will accelerate or retard the surface-runoff as it assembles to create the flood-wave.

The storm and accompanying rainfall are factors recognized as having physical limits within fairly well-defined regions of constant hydrologic characteristics. Current studies indicate that the likelihood of all the meteorological factors combining at their maximum in a single storm is of remote probability and that for such a phenomenon to occur in a critical position over a selected, relatively small basin approaches an impossibility. Therefore, if such a limiting or enveloping storm is to be considered beyond the probability of experience in a single storm-period of continuous rainfall, its estimation, or forecast, must rest upon the synthesization of the determinable factors at their upper limits.

The almost complete absence of hydrologic data on many basins for which important flood-control works must be designed has stimulated the development of a method of flood-flow estimation based upon the transposition of the great storms that have occurred in a given region to and in critical position over an individual basin. It is believed sound to assume that, looking into the future sufficiently far, every basin within a region will have experienced for every duration the greatest intensity of which the region is susceptible. It seems logical to assume, further, that in bringing to a particular basin every great storm that has occurred within the record-period of the region, the storm-record for the basin has been extrapolated into the future a considerable, though indeterminable, period. If now the greatest depths for selected durations are taken from the transposed storms and combined (that is, the greatest 6-hour depth from storm No. 4, the greatest 12-hour depth from storm No. 1, the greatest 18-hour depth from storm No. 3, etc.), the synthesized storm resulting will envelope all individual storms capable of occurring over the basin.

Forecasting the probable flood--As storm-magnitude increases and approaches the proportions of the maximum storm the flood resulting will approach the same relative order of magnitude principally because the great storms are accompanied by periods of antecedent rains that insure maximum runoff-conditions. The lesser storms, however, can occur coincidentally with either extreme of surface-wetness or dryness so that the storm to be expected once in ten years on the average may produce a flood of an entirely different frequency.

The forecast of the probable flood provides the basis for the evaluation of the accepted inadequacy of a structure and becomes the means for making the proper division of the ultimate cost of flood-control into (1) the first cost (cost of the completed structure capable of functioning safely for floods of lesser magnitude than the design-criterion) and (2) the replacement-cost (cost of rebuilding or repairing the structure in whole or in part as the result of damage inflicted by the less frequent floods above the design-criterion which may or may not occur within the life of the structure).

Forecasting the individual flood--We have discussed the forecasting of the "maximum flood" and the "probable flood," and the methods of estimating the magnitude and duration with which

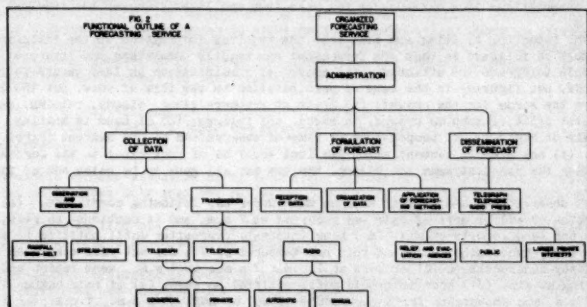
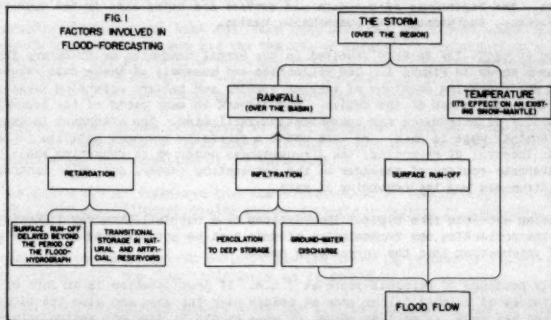
they will be reached or exceeded in the economic life of works or structures under design, or in the evaluation of damage to be sustained if such protective works are not provided or made large enough. In these cases the actual time of occurrence of the forecast flood is not determinable.

While the forecast of the "individual flood" is directed toward the same general objective--the elimination or reduction of flood-damage--its approach is one of preparedness rather than of protection.

The cost of a flood may be considered to embrace the following items: (1) Loss of human life; (2) damage to the public health; (3) damage to movable property; (4) damage to immovable property; and (5) intangibles, such as disruption of business and transportation. An accurate and timely forecast of an impending flood should eliminate the first, materially reduce the second and third, to some extent reduce the fourth by providing an opportunity to protect the less vulnerable areas, and in some degree reduce the fifth class of damage.

The forecast, to be effective, must be accurate and timely. Accuracy will depend on the adequacy of the data and the flexibility of the method of forecasting to allow for the use of the greatest number of factors. The period of forecast (the interval between the time of issuance and the time of arrival of the forecast stage or crest) will depend upon the promptness with which data are assembled, organized, and translated into terms of flood-discharge and stage.

The simplest method of forecasting is that based upon stage-relations--an estimated future stage at any point being reflected more or less consistently by the prevailing stage at a point upstream. This method meets conditions on the lower reaches of the larger rivers where stage-relations are usually stable and distances are sufficiently great to provide time for action on the forecasts as issued. The limitations of this method, when applied to tributary or headwater-



streams, are obvious. Among them are the instability of stage-relations with increasing slope, the impossibility of accurately combining flows in terms of stage, the relatively short concentration-period characteristic of such streams, and the difficulty of correcting for lateral inflow between stations. Under headwater-conditions the forecast to be at all effective must be projected from the time of falling rain. Runoff from melting snow must be taken into account. Seasonal, day-by-day, and even hourly changes in ground-surface conditions, as such affect the infiltration-capacity of the soil, must be evaluated.

The complexity of the problem of forecasting the individual flood is seen in Figure 1 in which the principal factors and their relationships are shown diagrammatically. To observe, record, transmit, receive, tabulate, and analyze them demands a closely organized service characterized by unremitting alertness, dependability of communications, simplicity of method, and the fortified judgment of trained and experienced personnel. The functional outline of such a service is shown in Figure 2. The various steps in the operation are as follows:

Administration--In the United States the flood-forecasting service to the public is conducted by the Weather Bureau. This service has been continuous on the larger rivers since 1892. The work is administered and the service rendered through 70 river forecasting-districts serving nearly 1000 cities, towns, and communities, which are now being supplemented by regional centers with the view of more effectively coordinating the forecasting procedure between districts. The inadequacies of the present service are reflected principally in too few rainfall and stream-gage reporting stations, lack of personnel trained in the development and application of advanced forecasting methods, and a limited use only of available aerological and meteorological services. However, plans are in course to expand and increase the effectiveness of the service by extending it into tributary and headwater-areas, providing the forecasting centers with necessary additional hydrologic data and developing refinements in forecasting methods and techniques. The discussion to follow does not reflect the service as it is now rendered in the greater number of river-districts. The beginnings of a modernized service are being made in the upper Ohio, upper Mississippi, Potomac, Sacramento, and Susquehanna basins.

Collection of data--The factors involved in the normal headwater or tributary forecasting problem have been shown in Figure 1. The collection and assembly of these data require a network of observation and reporting stations of varying spacing and pattern depending largely on the physiographic characteristics of the region. The network in many parts of the country is limited by the availability of attendance and communication-facilities. The attendant is usually a layman to whom a nominal wage is paid. He acts under a carefully prepared detailed instruction which fixes the interval of reporting, the circumstances under which reporting shall begin, primary and alternate routing of messages to the forecasting center, and which instructs him in the care of instruments and the recording of data.

The following excerpts from typical instructions to a rainfall-observer illustrate the detail in which the collection and transmission of data must be accomplished to secure an uninterrupted flow of information into the forecasting center.

"Take daily readings of rainfall-depth at 7 a.m. If precipitation is in form of snow, measure depth in inches of freshly fallen snow at points near the gage and also the total depth in inches of old and new snow, as well as amount of snow caught in gage and melted before measuring. Record your observations in a notebook as you make them and later transfer the readings to the official form.

"Stations reporting by telegraph will send the required information in the following order. This order must be followed so that the forecaster may readily understand and interpret all telegrams. Sample telegrams are attached. (a) Amount of precipitation in last twenty-four (24) hours, in words, not figures--in the case of precipitation in the form of snow, put the word 'snow' before the words for the amount; (b) state of weather--clear, cloudy, raining, snowing, etc.; (c) total depth of snow on ground, in words, not figures; (d) if snow is melting, state whether slowly or rapidly; (e) temperature at time of observation to the nearest degree, in words, not figures; (f) any general comment which you feel would be of real value to the forecaster, such as whether the local streams are rising, the ice has all gone or is going out of the local streams, etc."

"Special observations and reports will be made under the following conditions: (a) If forty-hundredths (0.40) or more of rain was recorded at 7 a.m. and it continues to rain, make observations and send reports at six- (6-) hour intervals thereafter until notified to stop; (b) if less than forty-hundredths (0.40) of rain was measured at 7 a.m., but rain continues and amounts to forty-hundredths (0.40) or more at 1 p.m., 7 p.m., or 1 a.m., send report and continue reporting at six- (6-) hour intervals until notified to stop; (c) if rain begins at any time after 7 a.m. and amounts to forty-hundredths (0.40) or more at 1 p.m., 7 p.m., or 1 a.m., send report and continue sending reports at six- (6-) hour intervals thereafter until notified to stop."

Communication-systems, both public and private, must be utilized to the fullest. The organized use of radio amateurs has proven a security against wire-line failure. Service-operated radio networks, including both automatic and manual transmission, are demonstrating their effectiveness and dependability in several parts of the country.

Formulation of forecast.--We have seen in Figure 1 the need to anticipate progressively throughout the course of a flood-producing storm the quantitative amount, duration, and sequence of a number of meteorologic and hydrologic factors and their combinations, which embrace the hydrologic cycle from the embryo storm in the form of converging air-masses of critical character and proportions, through rainfall and runoff to stream-flow. With our limited data-sources and our equally limited knowledge of the morphology of storms we cannot now forecast rainfall quantitatively with acceptable accuracy or consistency. We can, however, make full use of our meteorological and aerological services as outposts against the unheralded approach of flood-producing storms.

The stage is set for a flood by conditions prevailing throughout a period of critical length antecedent to heavy rainfall. The period varies with locality, the season of the year, and the nature of soil and cover. During the summer months relatively high rates of evaporation and transpiration result in near-maximum infiltration-capacities in the soil. The flow in the smaller streams is reduced to that wholly supplied from ground-water sources. Under these conditions appreciable quantities of rain can fall without creating flows of flood-proportions.

In contrast are the conditions of late winter and early spring. A snow mantle of high water-content may envelop the basin, or moderate but prolonged rains may have reduced the infiltration-capacity of the soil to a minimum. Evaporation is usually negligible and the demands of vegetation low. Under these conditions the initial flow in the streams being fed more rapidly from the raised water-table may be relatively high.

These considerations suggest that the flows from selected sub-basins could be used as indices to evaluate surface-conditions and the amounts of rainfall to be absorbed by the land through infiltration. The forecasting procedure should include a systematic means of assembling at the forecasting center a day-by-day evaluation of surface-conditions throughout the possible flood-season in terms of stream-discharge from watersheds selected as typical of the basin.

A six-hour reporting period is proving to be of workable length on river-systems of intermediate size. This allows two to three hours for the reception of data and three to four hours for the formulation and dissemination of the forecasts.

Rainfall-reports are so organized that the distribution of average depth for each six-hour period over the principal tributary basins can be determined rapidly by mechanical and graphical methods.

River-stage reports are received periodically and serve as indices of runoff-conditions and also to progressively plot the flood-hydrograph as it develops.

The goal in flood-forecasting toward which our efforts are bent is that of the maximum forecast-period or preparation-opportunity. The practicability of utilizing available meteorological facilities and modern techniques in approaching that goal is illustrated in the following description of a forecast-formulation as it might have been experienced under an expanded service. Figure 3 shows graphically the sequence of events to be anticipated in forecasting an individual flood. The storm of January 29 to February 3, 1939, over the Shenandoah Basin above Millville, West Virginia, has been chosen for the illustration.

Studies of rainfall-streamflow relations for the basin indicate an initial runoff-coefficient of about ten per cent. Figure 3 shows the progressive increase of the runoff-coefficient as the storm progressed.

The synoptic weather situation as of 7:30 a.m., January 28, 1939, indicates precipitation breaking out in the West Gulf area and moving northeastward toward the Appalachian Region.

The situation at 7:30 p.m., January 28, 1939, indicates a rapid northeastward movement of a well-defined moist tongue accompanied by copious rainfall.

Another area of cyclogenesis becoming evident at this time off the South Atlantic Coast is producing rainfall in the Carolinas and on the Georgia coast.

ILLUSTRATION OF AN IMPROVED METHOD OF HEADWATER-FORECASTING

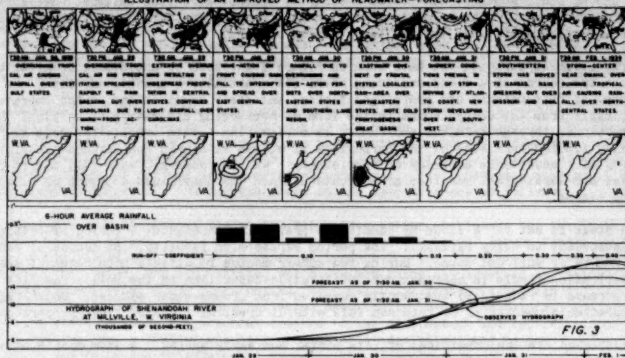
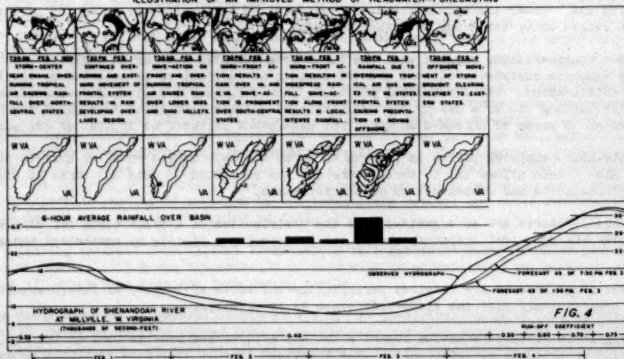


ILLUSTRATION OF AN IMPROVED METHOD OF HEADWATER-FORECASTING



At 7:30 a.m., January 29, 1939, the principal area of precipitation has entered the Appalachian Region. Rains continue along the South Atlantic Coast. The situation now indicates the necessity for preparedness at the forecasting center.

Weather-conditions at 7:30 p.m. confirm the forecaster's judgment as to the seriousness of the situation, justify the call for general reporting throughout the basin, necessitate the issuance of cautionary warnings, and warrant a trial estimate of rainfall to be expected in the next period.

The material in the hands of the forecaster, period by period, is displayed in Figures 3 and 4. From rainfall up to 7:30 a.m., January 30, it was possible to formulate an approximate forecast of the peak-stage. This was refined from data received at the end of the rainfall-period, 1:30 a.m., January 31.

However, it is to be noted that as early as 7:30 a.m., January 31, a region of cyclogenesis is developing over the Great Basin and the far Southwest.

At 7:30 p.m., January 31, the further development and movement of this disturbance presents a potential threat to the Appalachian Region, particularly since it follows so closely an appreciable rise in the Shenandoah.

The rains anticipated on January 31 have materialized over the basin by the morning of February 2, the greatest amounts falling between 7:30 a.m. and 1:30 p.m. of February 3.

It is to be noted that a forecast of the peak-stage was possible at 1:30 p.m., February 3, approximately 40 hours in advance of the arrival of the crest at Millville. Six hours later, at 7:30 p.m., February 3, after rainfall had stopped, this forecast was confirmed and refined as shown in the Figure, affording a practical time for the evacuation of the areas to be affected.

The dissemination of the forecast--it is the community's task to maintain an alert awareness of the flood-hazard and to educate the public to the advantages and economies of flood-preparedness. It is also the community's responsibility to develop well-organized plans for action during floods that are best accomplished through prearranged cooperation with the American Red Cross and the Corps of Engineers.

"If we had only known in time . . ." and "if we had only taken advantage of the warning . . ." are sounded in mournful echo after each disastrous flood. The Weather Bureau, with a real appreciation for the limitations of its service, has set about to so improve river- and flood-forecasting as to remove the reason for the first of these excuses which is admittedly accountable for much of the misery and preventable damage following in the wake of a flood. The lament for the disregarded warning voices that trait of character--the inability to profit by experience--that we decry in the individual but condone in our social structure. How like a comfortable sickroom convalescence is the latter days of relief and rehabilitation following a major flood-disaster. Many families have lost their homes but have for the first time through public generosity experienced the advantages of organized communal living. Mothers dispell their doubts regarding modern preventive medicine and many children enjoy for the first time that feeling of well being which grows with adequate nourishment.

We see only too often, after a flood has passed, the reaction of the public mind to a fallacious and dangerous optimism about the future--now that the flood is over, and homes and property rehabilitated, induced poverty and hardship are to be forgotten as quickly as possible. What accounts for this? It cannot be that the cost is not a very real one; it is both real and great, and it is borne directly by the individual and the taxpayer in dollars and cents. The explanation cannot be that violent death, permanent impairment of health, loss of estate, and social maladjustment have not left their mark, for these misfortunes are visited upon thousands of families in flooded valleys every year. The answer lies, no doubt, in the fact that human beings quickly adjust themselves to misfortune and accept too willingly the illusion that it will not visit them again.

The service, conducted so long as an established function of the Weather Bureau, is not spectacular and is taken by the public as a matter of course. Its difficulties are less well known. Inadequate facilities for gathering data of rainfall and stream-flow impose an undue dependence upon the personal judgment of the forecaster; failure of communications with outlying reporting stations in critical periods increases immeasurably the difficulties of accurate prediction. The Weather Bureau Office in Pittsburgh, during the peak of the flood of March 1936, disposed of nearly 8000 telephonic inquiries in one day. These, together with tremendous pressure from public and private interests, combine to create a situation that is far from conducive to efficient estimating.

While the flood-hazard is confined to the river-valleys it is by no means restricted to the spectacular great floods that periodically sweep down our principal rivers. Of the 168 months in the period 1924 to 1937, there were only 15 months in which there was not a damaging flood somewhere in the country, grossing the staggering annual loss of one hundred million dollars and a toll of nearly 100 lives. These are average figures, of course, that have been greatly exceeded in many of the years of record.

As the modern automatic fire-alarm system is to be credited largely with the immunity we now enjoy from the catastrophic conflagration which occurred all too frequently throughout the past half-century, so should a modernized flood-forecasting service pave the way to a more intelligent use of our river-valleys.

U. S. Weather Bureau,
Washington, D. C.

STREAM-FLOW FORECASTING BY SNOW-SURVEYING

George D. Clyde

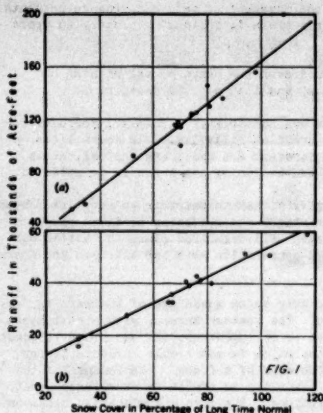


FIG. 1

oped and first used by Dr. J. E. Church of the University of Nevada.

Following Dr. Church's pioneer work in forecasting flows from snow-surveys, the Utah Agricultural Experiment Station became actively interested in the subject in 1923, and in 1930 active cooperation with the Forest Service, the Weather Bureau, and the Utah State Engineer was developed. By 1935 the activity had grown to such an extent that coordination of the efforts of the various States became necessary, and the Bureau of Agricultural Engineering, United States Department of Agriculture, became an important cooperator.

If it were possible to predict the discharge for any day it would be possible for the water-commissioner to deliver water in terms of acre-feet, and the water-master in turn to deliver water to users in terms of acre-feet per month. This would make possible a "rotation-on-demand" system of deliveries that would greatly increase the efficiency of water-use.

A study of typical Utah streams not regulated by storage reveals a striking uniformity in the slope of their daily hydrographs during the falling stage and the critical low-water period (July-September).

From an examination of the daily hydrographs it was found that after the river-discharge had reached a maximum (shortly before the final disappearance of snow from the watershed), it declined sharply. In every case the decline appeared to follow a definite law regardless of whether the year was one of high or low flow.

It was found that rectangular hyperbolas could be drawn that would coincide almost perfectly with the forecast curves, but to keep their axes parallel to the axes of the hydrograph it was

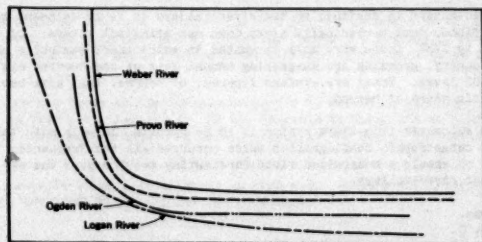


FIG. 2—CURVES FOR DAILY FORECASTS, FOUR UTAH STREAMS

Storage of water in the form of snow makes possible an advance determination of the probable water-supply. Forecasts may be expressed in terms of acre-feet for specific periods, or in terms of discharge in cubic feet per second for specific dates. Forecasting the total supply over a given period, on the basis of snow-surveys, is now well established, but a determination of the probable discharge for any specific date during the critical runoff-season is more difficult. On streams having ample surface-storage, a seasonal forecast is all that is necessary. However, where the water cannot be stored, but must be used as it comes, it is extremely valuable to know the time of its occurrence.

Snow-surveying for stream-flow forecasting is not predicated upon a determination of the quantity of water on the watershed at the end of the precipitation-season and the quantitative amount of the losses. Rather it assumes that a normal snow-cover will produce a normal runoff. This has sometimes been called the percentage-method of forecasting, and was developed

necessary to rotate them through a small angle. In addition, a constant had to be added to the equation to compensate for the vertical shifting necessary to bring the hydrographs into coincidence. The result was a forecast equation of the form, $y^2 + Ax - x^2 = B \pm C$, in which y is the discharge in cubic feet per second at any date and x is the time-interval in days between date of forecast and date for which discharge is desired.

Forecasts of daily discharge from snow-fed streams, during the spring recession and summer low-water periods, can be made if the flow-characteristics are known and the results are well within the limits of accuracy required for application to practical use. The forecasts can be made far enough ahead of the stream-flow occurrence to be used as a basis for distribution of water under the demand system.

Water-supply forecasts do not provide more water, nor do they prevent or reduce natural water-losses; but a knowledge of the extent and distribution of the supply in advance of its occurrence does make possible a more efficient utilization and is therefore an important factor in any water-conservation program.

[Note: The above is a summary of a more complete paper published in full in "Civil Engineering" (v. 9, No. 4, pp. 237-239, April 1939); Figures 1 and 2 are reproduced by courtesy of that magazine.--Ed.]

Utah State Agricultural College,
Logan, Utah

ESTIMATING MAXIMUM FLOOD-FLOW AS A BASIS FOR THE DESIGN OF PROTECTIVE WORKS

Gail A. Hathaway

(1) It has been recognized by the Federal Government, within recent years, that destructive floods upon the rivers of the United States constitute a menace to national welfare. The River and Harbor Acts of March, 1925, and January, 1927, resulted in what are generally known as H.D. "308" reports covering the principal drainage-systems in the United States. The "308" reports were followed by Flood-Control Acts, authorizing projects throughout the United States, such as reservoirs, levees, channel-improvements, river cut-offs, diversions, debris-basins, flood-ways, and flood-walls. In addition to the authorization of definite flood-control projects, the Acts provide for preliminary examinations and surveys for flood-control at approximately 440 localities throughout the country. Prosecution of this work is by the War Department, under the supervision of the Chief of Engineers.

(2) The size, character, and method of construction and the plan of operation of flood-control units are determined to a major extent by hydrological studies. The economic importance of reliable and comprehensive hydrological data and methods have been increasingly emphasized by the national flood-control undertaking. It is not to be overlooked that future operation of works now under construction and the ultimate expansion of the system will demand greater refinements in basic data and methods of computations. The War Department has recognized the urgent and immediate need for a greater knowledge of the meteorological, geographical, and topographical conditions determining limiting storm-conditions in all sections of the country and the extension and improvement of facilities for measuring rainfall and stream-flow.

(3) The problem of most immediate importance is the determination of limiting storm-conditions affecting spillway requirements for proposed dams. This is particularly important inasmuch as the majority of dams authorized for construction are located upstream from important centers of population that would suffer great loss of life and property should the dam fail. The most reliable basis for establishing limiting storm-conditions in various sections of the country is the detailed analyses of past storms with a view to determining the meteorological phenomena involved and the formulation of rational concepts for estimating reasonable modifications of meteorological factors that might have resulted in critical precipitation-rates in the region considered.

(4) Accordingly, arrangements were completed in July, 1936, with the Weather Bureau for a meteorologist to be temporarily assigned to the Office of the Chief of Engineers for studies of storm-potentialities in various sections of the United States. In December, 1937, plans were made for the transfer of War Department funds to organize a Hydrometeorological Research Section in the River and Flood Division of the Weather Bureau. The scope of the present program of the Engineer Department has made it necessary to expand the Hydrometeorological Section to 24 persons.

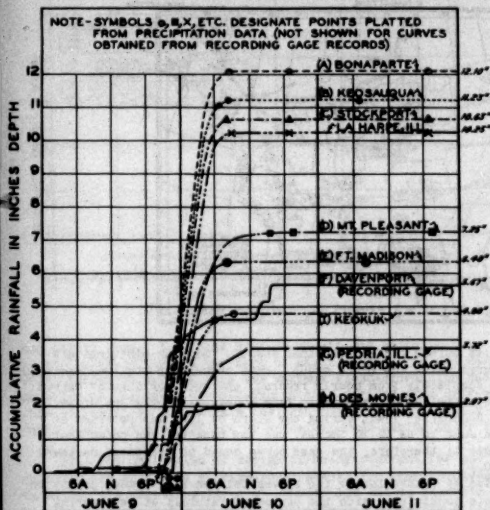


FIG. 2--MASS RAINFALL CURVES FOR STORM OF JUNE 9-10, 1905, IN IOWA

(b) Precipitation-data including notes regarding times of beginning and ending, character of the day and any other pertinent notes are transcribed from original observers' records to convenient forms. Similar data are assembled from other sources, such as published and unpublished reports, newspaper files, and occasionally by interviews with witnesses in the storm-area.

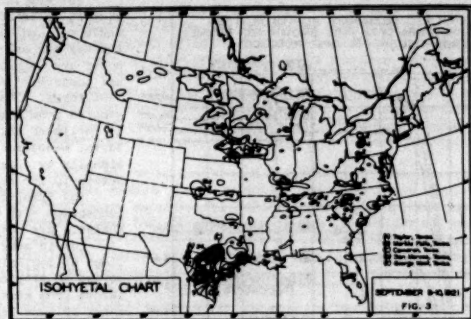
(c) Synoptic maps required in connection with the meteorological analysis are prepared.

(d) In some instances, the times of beginning of rainfall reported on original records, obtained from news accounts or indicated by gage-heights on small streams, are plotted on a map and isochrones interpolated that give an index to the time of beginning of heavy rainfall at stations where such information was not recorded.

(e) A group of four to six neighboring stations are selected that show approximately comparable quantities of total rainfall and are located in regions of reasonably similar topography. The accumulative rainfall at successive recording times are plotted for each of these stations on a trans-

Table 1--Precipitation-data for storm of June 9-10, 1905, in southeastern Iowa

Station			Day of June 1905	Precipitation-data			
Location	Key letter for Fig. 1	Time 24-hour rainfall was measured		Time of beginning	Time of ending	Depth of rainfall in 24 hours ending at recording time	Accumulative rainfall at recording time
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		h m		h m	h m	inch	inch
Bonaparte	A	7 00 pm	9	8 30 pm	.....	0	0
			10	.....	8 30 am	12.10	12.10
			11	.....	.....	0	12.10
Keosauqua	B	7 00 am	9	8 30 pm	.....	0	0
			10	.....	8 30 am	11.09	11.09
			11	.....	.....	0.14	11.23
Stockport	C	7 00 pm	9	8 00 pm	.....	0	0
			10	.....	8 00 am	10.63	10.63
			11	.....	.....	0	10.63
Mt. Pleasant	D	6 30 pm	9	2 00 pm	6 15 pm	0.05	0.05
			9	DN	.....	.....	.....
			10	.....	3 30 pm	7.20	7.25
Ft. Madison	E	8 00 am	9	8 00 pm	.....	0	0
			10	.....	8 00 am	6.40	6.40
			11	.....	.....	0	6.40
La Harpe (Ill.)	K	7 00 pm	9	9 00 pm	.....	T	0
			10	.....	9 00 am	10.25	10.25
			11	.....	.....	0	10.25



parent form to permit comparisons with curves plotted on other sheets. Similar plottings are made for other groups of stations surrounding the first group. Mass curves for stations equipped with recording rain-gages are drawn completely from hourly records, and such portions of curves for non-recording stations as can be established immediately from observers' notes are drawn. (For example, the total rainfall at Bonaparte, Iowa, during the storm of 1905 was recorded at the regular observation at 7 p.m. on June 10 as 12.10 inches, but the observer had noted that the rain ended at 8:30 a.m.--see Table 1; therefore, the mass curve could be projected backward horizontally to 8:30 a.m. on June 10.)

(f) The mass curves are completed by interpolating the curves between established points in such a manner as to reflect reasonable consistency with the period of rainfall at neighboring stations, the movement of fronts and waves as determined from meteorological analyses, and such additional data as are available in the specific instance.

(9) Inasmuch as intense rainfall during the storm of June 9-10, 1905, was confined to one principal period of rainfall that was readily ascertained by reference to the original observers' records, construction of mass rainfall-curves shown in Figure 2 was fairly simple. However, it is significant that the storm was found to be of approximately 12 hours' duration, whereas published records indicated that the storm covered a two-day period. The construction of reasonably accurate mass rainfall-curves is more difficult for protracted storms that are characterized by marked changes in rainfall-intensity and movements of precipitation-centers, and may require the detailed procedure outlined above.

(10) Maximum storms in the southern United States differ materially from the more northerly storms, in that the duration of intense precipitation may be several times as long and the area covered by the intense rainfall may be many times as great. However, evidence is not conclusive that the rate of rainfall over a small area in a period of a few hours is appreciably greater than has occurred in some northern storms. The excessive precipitation in Texas near the Gulf of Mexico during September 8-10, 1921, provides a comparison of intense summer storms in the Gulf Region with those of the middle west (see Fig. 3). It will be observed that the mass precipitation-curve plotted from the recording rain-gage at Taylor, Texas (Fig. 4), shows that almost 20 inches of precipitation fell in the 12-hour period between 7:00 p.m. September 9 and 7:00 a.m. September 10. Most of the rain for the total storm occurred in less than 36 hours. The rainfall averaged ten inches over an area of about 20,000 square miles.

(11) Mass rainfall-curves have proven very valuable in the reconstruction of hydrographs of actual floods for the purpose of analyzing runoff-characteristics of streams. Figure 5 was prepared from a chart presented in a hydrological report by the Pittsburgh Engineer District. The mass rainfall-curves reflect the principal variations in intensity during the storm that produced the greatest flood of record in the Loyalhanna Creek Basin in western Pennsylvania. From these curves, isohyetal maps were prepared and the average rainfall over the Basin was computed for successive 12-hour intervals of the storm. The drainage-area involved was 265 square miles. The 12-hour rainfall-quantities were then shown above the plotted hydrograph in proper time-relation (Fig. 6). The surface-runoff was next determined and associated with the rainfall that contributed appreciably to surface-runoff. A distribution-graph was computed that reproduced satisfactorily the recorded hydrograph when applied to the estimated 12-hour increments of rain

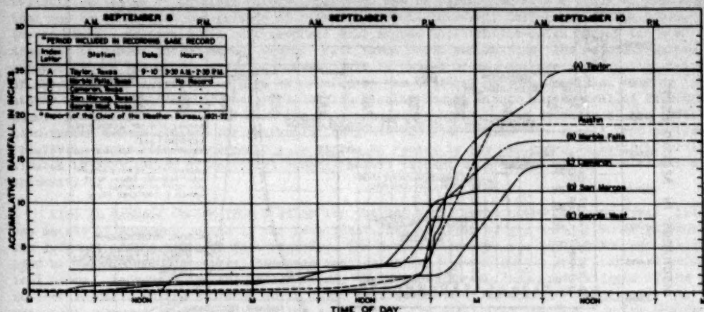
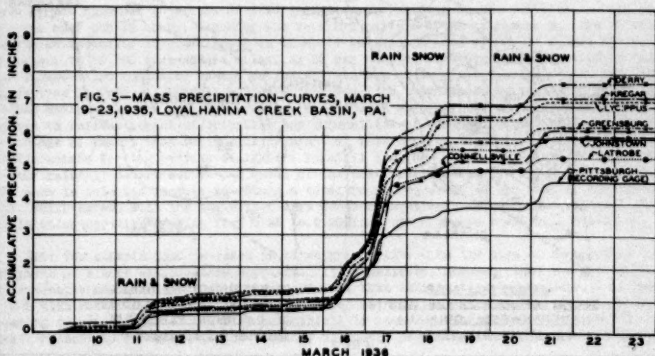


FIG. 4—MASS PRECIPITATION CURVES FOR TEXAS STORM OF SEPT. 8-10, 1921

and melted snow. The total surface-runoff was approximately five inches from the drainage-area of 285 square miles, 65 per cent of which occurred in one 24-hour period. It was found that the unit-hydrograph derived from the maximum flood-hydrograph had a peak considerably higher than expected on the basis of unit-hydrographs derived from hydrographs representing approximately one inch of runoff or less. This has been found to be generally true in the studies of relatively small basins in which effect of valley-storage during major floods is not extremely high.

(12) The derivation of design flood-hydrographs for use in the determination of spillway-capacity and surcharge storage-requirements for dams involves the very important problem of determining the proper estimate of runoff that can be expected from the hypothetical design-storm. The design-storm estimate is usually obtained either by direct transposition of some actual storm of record in the vicinity or by derivation of a synthetic storm on the basis of meteorological studies involving the analyses of actual storms in the region to determine limiting conditions. The transposition of the design-storm over a given basin in practically all cases involves the assumption of rainfall-intensities several times as severe as have ever been recorded in the basin. Consideration of the absorptive properties of the soil demonstrates conclusively that runoff-factors derived from rainfall-runoff quantities of small magnitude have little direct application to the determination of runoff from the transposed, or hypothetical design-storm. Application of the infiltration-theory, with modifications in certain instances, appears to offer the most reliable method of approach. The methods outlined by Horton, Sherman, Langbein, and others, for determining at least approximate indices to the minimum infiltration-capacities for large drainage-areas afford a more rational basis for estimating runoff from design-storm



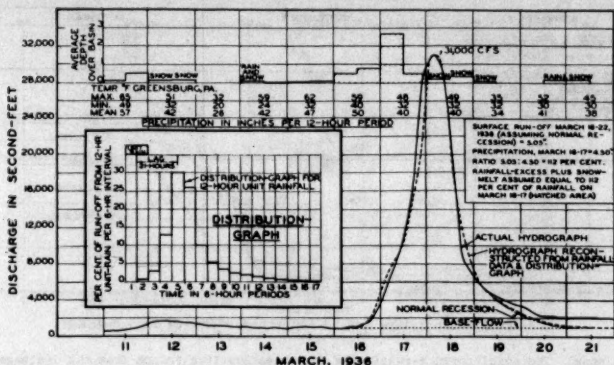
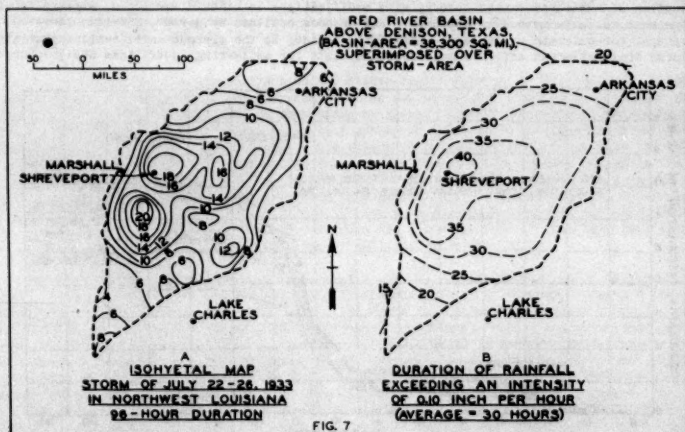


FIG. 6—ANALYSIS OF FLOOD-HYDROGRAPH AT NEW ALEXANDRIA, PA.,
LOYALHANNA CREEK BASIN

rainfall of various intensities and durations than the old methods involving runoff-factors. Application of the infiltration-theory to small basins is fairly simple, but application for determination of runoff from design-storms over large drainage-areas involves several difficult problems, particularly when infiltration-rates are high. In order to apply the infiltration-theory in estimating the volume of runoff from a design-storm, it is necessary to know, in addition to the minimum average infiltration-capacity of the basin, (1) the area covered by rainfall of an intensity exceeding the minimum average infiltration-capacity of the basin, and (2) the duration of significant rainfall. It is apparent, therefore, that design-storm estimates should include not only the volume of rainfall that may be expected in successive intervals of time, but also the critical rainfall-pattern and duration of significant rainfall during each unit-period of the storm. In view of the innumerable variations that the precipitation-pattern and intensity may assume during a prolonged storm, it is sometimes impracticable to make reliable estimates for both of these factors for all intervals of the design-storm. However, reasonably



reliable estimates of critical rainfall-patterns can be formulated from a study of past storms that may be applied to the periods of highest rainfall-intensity during the design-storm. Also, it can usually be considered that rainfall will exceed infiltration-rates during the most intense 6- or 8-hour period of the storm. With these basic assumptions, the rainfall-excess, or surface-runoff may be estimated as the rainfall in excess of the average infiltration-capacity of the soil over an effective area delineated by the critical rainfall-pattern. During intense storms the major portion of the precipitation usually occurs within an interval of 12 hours or less. Determination of runoff from the most intense rainfall-period by means of the infiltration-theory offers a basis for extrapolation above empirical data. The runoff from periods of relatively light rainfall comparable to storms of record in the basin may be satisfactorily estimated by application of empirical runoff-factors without knowing the aerial distribution or intensity.

(13) An example chosen from a study for the Red River Basin above Denison, Texas, illustrates one method of approach, which is far from ideal, but at least offers some definite guidance to the judgment of the engineer (see Fig. 7). The design-storm for the Denison Project was developed by the Hydrometeorological Research Section of the Weather Bureau from a special meteorological study. In developing the design-storm, the Weather Bureau based the estimate of the maximum 96-hour rainfall on the storm of July, 1933, that occurred in northwestern Louisiana. It may be reasonably assumed, therefore, that the duration of the significant rainfall during the design-storm might be at least as short as recorded during the actual storm of 1933. Mass precipitation-curves for all non-recording rainfall stations within the storm-area and one mass curve from a recording gage at Shreveport, Louisiana, near the storm-center, were used in determining the average duration of significant rainfall during the storm of 1933, following a method similar to that outlined by Langbein in connection with the determination of infiltration-capacities. The average duration of rainfall exceeding an intensity of 0.10 inch per hour over an area equivalent to the Red River Basin above Denison was only 30 hours, although the storm covered a 96-hour period.

(14) From an analysis of a large number of actual hydrographs for streams in or near the Red River Basin it was determined that a reasonable value for the minimum average infiltration-capacity for the drainage-area above Denison would be 0.20 inch per hour, although the value during the initial periods of rainfall might be somewhat higher. The assumption of a uniform average infiltration-capacity of 0.20 inch per hour during the indicated 30-hour duration of significant rainfall would be comparable to a loss of 6.00 inches, or to a runoff of 47 per cent of the total rainfall of 11.3 inches. A uniform average infiltration-capacity of 0.25 inch per hour would correspond to a loss of 7.5 inches or to a runoff of 34 per cent of the total rainfall. On the basis of these results it was concluded that the overall runoff from the design-storm should be about 40 per cent of the 96-hour rainfall.

(15) The critical pattern for the maximum 12-hour rainfall of the design-storm, as developed by the Weather Bureau from a study of actual storms, is shown in Figure 8. In view of the intensity of the rainfall indicated, it is logical to assume that precipitation would be continuous for the entire 12-hour interval. With these assumptions, the runoff from the most intense periods of rainfall may be estimated on the basis of the infiltration-theory. The runoff was taken as the rainfall in excess of 2.40 inches, corresponding to an infiltration-rate of 0.20 inch per hour for 12 hours, assuming the rainfall-pattern shown by Figure 8. The rainfall exceeding an intensity of 2.40 inches in 12 hours covered an area of 20,200 square miles and was equivalent to 70,700 inch-square-miles, or 50 per cent of the total precipitation of 142,000 inch-square-miles indicated by the estimated rainfall of 3.7 inches average over the total Basin. Runoff from periods of rainfall approximately equal to intensities witnessed in actual storms in the Red River Basin and adjacent areas were estimated by empirical runoff-factors, which may be assumed to reflect aerial distribution and intensities of rainfall during moderate storms. The percentage of runoff from periods of rainfall of intermediate intensities was interpolated between runoff-factors for the periods of lighter rainfall and the percentage runoff from the maximum 12-hour rainfall determined on the basis of the infiltration-theory. Reasonable adjustments were made in selected factors to obtain a total runoff equal to 40 per cent of the 96-hour rainfall, which agrees with the assumption of a 30-hour duration of significant rainfall and an infiltration-capacity varying from 0.25 to 0.20 inch per hour, as previously discussed.

(16) The example just reviewed is cited principally with the hope of encouraging the development of a more satisfactory approach. It is believed, however, that the procedure followed is reasonable and consistent with the known fact that infiltration-losses vary to an important extent with rates, duration, and distribution of rainfall. In most semiarid regions information relating to percentages of runoff from rainfall is based on storms of low or moderate intensities. Failure to recognize the probability of runoff-percentages materially exceeding recorded

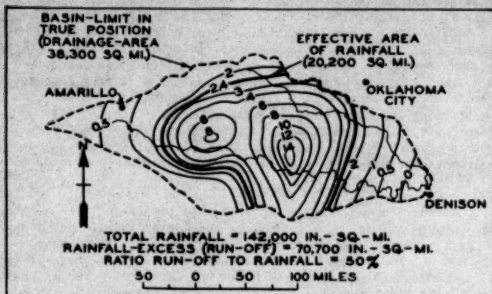


FIG. 8—ESTIMATED CRITICAL PATTERN OF MAXIMUM 12-HOUR RAINFALL DURING DESIGN STORM

plots should reveal valuable data regarding the infiltration-characteristics of soils, but information on infiltration-capacities derived from rainfall-runoff data for large basins appears to have the most direct and practical application to general hydrological computations.

(17) In connection with hydrological computations related to the design of protective works, valley-storage, flood-routings, and unit-graph computations of course play a very prominent part. However, these subjects have been very extensively and ably treated by a great number of authorities.

(18) In the review of a large number of engineering reports requiring prompt decisions, a concise presentation of facts is of vital importance. Graphical presentations are particularly adaptable to hydrological problems. A form of chart that has proven very useful in the determination of spillway-capacity and freeboard-requirements for dams is illustrated by Figure 9. Figure 9-A indicates the extreme maximum water-surface elevations that would prevail if floods should occur greater than the synthetic flood derived from estimated critical rainfall- and runoff-conditions. The chart offers a means of judging the ultimate factor of safety represented by freeboard-allowances. The performance-characteristics of different sizes or types of spillway may be clearly demonstrated, as well as the results of different plans of operation. In Figure 9-B, the inflow and outflow of reservoir corresponding to floods equal to various percentages of the basic synthetic hydrograph are represented. The relative slopes of the inflow- and outflow-

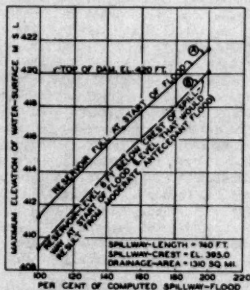


FIG. 9A

CURVES SHOWING MAXIMUM RESERVOIR-LEVELS THAT WOULD BE ATTAINED DURING FLOODS EQUAL TO VARIOUS PERCENTAGES OF COMPUTED SPILLWAY-FLOOD

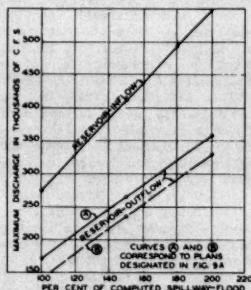


FIG. 9B

CURVES SHOWING RESERVOIR-INFLOW AND OUTFLOW CORRESPONDING TO VARIOUS PERCENTAGES OF THE COMPUTED SPILLWAY-FLOOD

WAPPAPELLO DAM, ST. FRANCIS RIVER, MISSOURI

curves give an index to the importance of accurate determination of peak flood-discharges. If the inflow and outflow-curves are approximately parallel, a great deal of effort may be justified to obtain the most accurate estimate of peak-inflow possible, since a small error in the computed peak-rate of reservoir-inflow would introduce a relatively large error in the determination of maximum reservoir-level. On the other hand, if the reservoir-storage and spillway-capacity are such that the slope of the outflow-factor of safety-curve is flat compared with that for inflow, then an appreciable error in the determination of the peak-inflow will not change the computed maximum reservoir-level to an important extent; hence less importance may be attached to precise computation of peak-flows.

(19) In preparing estimates of critical flood-conditions that determine the spillway-capacities and freeboard necessary for the safety of large dams and important protective works, a very conservative attitude should prevail. Experience of the past half-century has necessitated successive revisions upward in estimates of maximum probable floods that were considered safe when they were originally prepared. There is no apparent justification for assuming that we can now accurately predict critical flood-conditions. Factors of safety are necessary for security. Provision of an adequate factor of safety does not usually increase the return from the investment in protective works; it simply constitutes insurance against destruction and disaster as the result of unforeseen conditions. The cost of providing an ample margin of safety above the capacity necessary for apparent needs is, in the vast majority of cases, less than the cost of fire insurance on important buildings representing investments comparable to the cost of major flood-control works. The business man is not considered unreasonable for spending substantial sums for fire insurance simply because the building may never burn down. The increasing development in river-valleys of the United States will demand many additional flood protective works, which in turn will encourage further development. In order that these protective works may serve their purpose by safeguarding the lives and property of those who place confidence in the judgment of engineers, liberal factors of safety perhaps beyond values that seem reasonable on the basis of existing records will be essential in the design of every important structure.

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RELATION OF HEADWATERS-CONTROL TO THE NATIONAL PROGRAM OF FLOOD-PROTECTION

Arthur C. Ringland

Federal policy and program--Congress, in recognition of recurrent flood-history affecting the general public interest, has projected a long-range program and policy for the control of destructive floods. It has declared that such protection is a public responsibility and therefore a proper activity of the Federal Government in cooperation with the States and local public agencies. In the enabling flood-control legislation of 1936, the amendment of 1937, and the Flood-Control Act of 1938, Congress has prescribed procedures for the establishment of the national flood-control program. These enactments are the authorities which direct the Secretary of War and the Secretary of Agriculture to carry out an integrated and correlated program for which expenditures have been authorized over a five-year period, and appropriations made available for the fiscal years 1938 and 1939.

Division of responsibility--It is well known that the War Department is actively engaged in the construction of major engineering works for the control of flood-waters through the construction of storage- or detention-reservoirs, flood-walls, levees, and channel-improvements. Such works, immediately operative in the protection afforded to lives and property, are often referred to as downstream engineering.

But it is not so well known that the Department of Agriculture is charged with the so-called upstream engineering of the national flood-control program--that is for auxiliary measures of headwaters-control necessary to complement the downstream engineering works to retard the floods of minor feeder-tributaries, and effect soil-stabilization, revegetation, and reforestation of slopes which accelerate storm surface-runoff. Such works of minor hydraulic engineering, soil-surface engineering, and land-use adjustments on farms, pastures, and woodlands, are intended to protect and further the usefulness of the downstream engineering structures by increasing the effectiveness of the storage-capacity of reservoirs through the retardation of runoff, decreasing the rate of siltation and by reducing the deposition of erosional debris in river-channels or upon valuable land. The stability of rural economy is promoted at the same time through the protection of farmlands from top-soil erosion-loss and pasturage and woodlands from abusive ex-

plotation. It will be seen that the Department's major problem of headwaters-control is first the physical job of corrective measures of engineering and conservation, and, second, the application of economic and social adjustments in land-use through public administration or regulation, or cooperation with farmers and other owners. This paper is confined to the hydrologic phases of the problem.

In broad terms, there are two major types of flood-producing storms: One that is created by gentle rains of long duration covering wide areas and great drainage-basins, and one that is violent, of high intensity, of short duration, and covering but a small area. It is this last type that is of common occurrence at high elevations; it is the type that is responsible sometimes for loss of life, and generally responsible for the origin of much damage because of the impact of the rainfall, the accelerated velocity of the runoff, and the attrition of certain soil-types causing siltation and sedimentation through water-borne erosional debris. The Department's surveys therefore are directed to the flood and silt-source tributaries of watersheds, which, because of the precipitation-phenomena of the region and the nature of the terrain, are particularly subjected to the effects of accelerated storm surface-runoff. For example, these include watersheds of the Upper Susquehanna, the Appalachian slopes of the Ohio Basin, the lower reaches of the Upper Mississippi and Missouri River basins, the Ozark-Ouachita highlands, the White and Arkansas basins, the Colorado and Rio Grande basins, and Southern California drainages. It is the high and small drainages of the tributaries of these watersheds that need first attention and where the problem of control is difficult because of repeated torrential rains of high intensity and short duration and their effect on the soil-mass.

Major problems--Unhappily, our study of available records reveals that detailed knowledge of rainfall and stream-flow is almost non-existent when applied to small drainage-areas up to 200 square miles. Yet, so long ago as 1922, G. H. Matthes pointed out in the Proceedings of the American Society of Civil Engineers that small streams have not been taken seriously enough and that the absence of reliable data is appalling.

In order to lay a factual base for headwaters-control as a part of the national flood-control program and to justify operations on a technically and economically sound basis, adequate hydrological information must be obtained where deficient. Particularly rainfall-records at high elevations where our flood-troubles begin are lacking, as well as adequate records of snowfall on mountain slopes, evaporation, and volume and quality of stream-discharge. Rainfall-and-runoff relationship must be established for headwaters-drainages if flood-potentials are to be appraised intelligently. This appraisal in turn demands the consideration of the types of flood-producing storms each of which may be the result of wholly unrelated phenomena. There is also to be considered the effect of these storms and the varying intensities of their rainfall on the rate and percentage of runoff from the types of soil involved and the capacity of these soils for absorption.

Hydrologic studies--In order to meet these necessities for adequate hydrologic information for the small watersheds included in the flood-control program, the Department of Agriculture, through the Hydrometeorological Section of its own Weather Bureau, is developing a study of flood-producing storms at high elevations, their intensities, frequencies, and their distribution. The Department is fortifying these studies of storm-design by the installation of a number of automatic rain-gages and establishing snow-courses or stations integrated with the base network of the Weather Bureau. Supplementing these studies of precipitation, there is the necessity to determine the capacity of the soils of given watersheds for infiltration of surface-waters, and the artificial means of adding to their natural storage-capacities in order to reduce direct runoff. Observations are under way through the use in the field of artificial rain-makers under typical conditions.

With a knowledge of local rainfall-conditions and of the soils affected, we must know the volume, stage, and quality of the stream-discharge of the small tributaries. The Department is therefore cooperating with the Geological Survey in the establishment of stream-flow gages, and the obtaining of information on the accumulation of sediment brought downstream by the turbid waters of the direct runoff.

This program and the studies outlined cover the major problems involved in the determination of basic information on the hydrologic cycle as it relates to the national program of flood-protection which the Department of Agriculture is charged to undertake in correlation with the Army Engineers under the authorities of the enabling Flood-Control Acts of 1936 and 1938.

U. S. Department of Agriculture,
Washington, D. C.

THE METEOROLOGICAL PHASE OF FLOOD-FORECASTING

H. R. Byers

Forecasting flood-conditions by means of synoptic weather-charts and other meteorological information is one of the more recent adaptations of modern synoptic meteorology. In the brief period in which it has been followed, notably in the Los Angeles County Flood-Control District, it has proved to be an extremely important part of any flood-control program.

The forecasting of rainfall has been carried on by the various governmental meteorological services ever since the perfection of the telegraph permitted the preparation of synoptic or instantaneous weather-charts. These forecasts have been issued for general public use and from long experience it has been found impractical to specify the actual amount of rainfall to be expected or to issue superseding, perhaps contradictory follow-up forecasts at frequent intervals. However, the experienced, trained forecaster has weather-diagnoses and prognoses which, although of too uncertain a nature to give to the public, can be of considerable value to the flood-forecaster.

What the flood-forecaster wants--The flood-forecaster wants from the meteorologist certain types of information, some of which are as follows: (1) The approach of flood-producing rains as far in advance of their occurrence as possible, in order that the period of preparation for the operation of control-works, evacuation, and protection may be most effective; (2) the time that rainfall will reach its peak-intensity and approximately where; (3) the total amount of rainfall; (4) the time the rainfall will end; (5) the temperatures existing during the precipitation as they may affect thawing.

Other information includes the vertical distribution of temperature in mountainous areas, wind-velocities over storage-lakes, possibilities of freezing following the flood-rains and many other types of information, depending on the peculiar local problems to be dealt with.

The difficulties of furnishing this information--In the first place, it has to be admitted that completely reliable information of this sort cannot be issued more than a few hours in advance. In spite of the advances that have been made in forecasting, the day of 100 per cent verification of forecasts, even those for just a few hours ahead, is far from achievement. At first glance, it appears that it should be a simple matter to predict the weather-conditions at a particular place in a country comparatively well served by an organized reporting service as eastern United States merely by extrapolating the movement of storms moving in from the west, because it is known that weather travels from west to east. However, during this eastward displacement so many new complications such as accelerations, decelerations, frontogenesis, cyclogenesis, frontolysis, anticyclogenesis, deepening, filling, subsidence, convergence, and many and varied disturbances in the general circulation can affect the moving systems, that the forecasting of precipitation with certainty becomes extremely difficult. It is obvious, then, that the flood-forecaster should keep continuously in direct personal contact with the weather-forecaster in order to obtain from him whatever advice concerning the future weather he can give as the storm approaches.

Background for the possible solution of these difficulties--The advances that have been made in our knowledge of the weather through the introduction of frontal and air-mass analysis has been widely publicized. This method, developed originally by the Scandinavian meteorologists, has been adopted already in several hydrologic applications. It has facilitated the determination of flood-limits and flood-expectancy for particular drainage-basins by furnishing a more accurate and detailed knowledge of storms and the feasibility of their transposition. The new meteorology furnishes also a more secure basis for estimation of synthetic storms. Not only have the air-mass and frontal theories themselves been important in this development but, most of all, the advanced concepts of synoptic and dynamic meteorology which have been passed on to the younger meteorologists of this new school of thought have done much to stimulate an activity in this new field which is now being designated as hydrometeorology. However, the application of this knowledge and these skills to the routine forecasting of flood-rainfall is only entering the trial stage.

The air-mass and frontal concept is based on the recognition of large currents of air having different origins and called air-masses. Air-masses from the warm, damp region of the Gulf of Mexico appear in sharp contrast to those from the northern continental region and these contrasting characteristics are maintained by the air-masses as they move from their places of origin. Where two masses of air of such contrasting qualities meet, there is no direct mixing, but rather a discontinuity-surface is formed between them. This discontinuity-surface is called

a "front." The front orientates itself in such a way that the colder air-mass underlies the warmer air, but on account of the deflection due to the Earth's rotation, the line of separation slopes upward. The warm air ascends these slopes and, just as warm, moist air produces precipitation as it ascends the slope of the mountain, so does it produce rain or snow falling downward through the underlying wedge of cold air. The precipitation, as in the case of ascent over mountains, is caused by the cooling due to expansion of the air against the decreasing pressures with altitude. The cooling reduces the temperature of the water-vapor to its saturation-point.

In addition to giving the picture of the storm-mechanism in greater detail, the analysis of fronts and air-masses makes it possible to apply approximate equations to give the displacements of fronts, low-pressure and high-pressure areas, to show regions of cyclogenesis, frontogenesis, deepening, filling, convergence, and divergence. New methods of charting upper-air conditions, so important in determining rainfall-conditions, have been developed, including the use of the isentropic chart, which shows the motion of the air in the vertical as well as the horizontal component.

What can be done at present?--The discussion above may present a discouraging picture of the immediate possibilities of the meteorological phase of flood-forecasting. However, it has been demonstrated that a well-trained meteorologist and hydrologist working in close cooperation can achieve remarkable success with the meteorological information at hand.

While the established flood-forecasting service of the Weather Bureau utilizes the general weather-service in formulating forecasts, a more highly developed and specific example of the possibilities of this work--the flood-forecasting in the Los Angeles County Flood-Control District--may be cited. I am indebted to Eugene Bollay, now of the Weather Bureau in Washington, who recently served as a meteorologist of the Los Angeles District, for furnishing an outline of the work performed there.

The Los Angeles County Flood-Control District has actually used synoptic weather-forecasting methods successfully since 1934; the type of forecast required and its application in this field can perhaps be best understood by reviewing the method as used in Los Angeles. The same method can be applied elsewhere in this country with perhaps even more dependability since the synoptic data which have to be used on the Pacific Coast are composed almost exclusively of reports from vessels which are usually very limited. In other portions of this country greater success should result due to the greater amount of upper-air data available as well as surface synoptic data.

The forecast as issued consists essentially of two main parts. The first part (a) is a short-range forecast which gives the weather-conditions that are expected in great detail during the following 12 to 24 hours. During actual storm conditions supplementary forecasts are issued whenever more data become available which indicate change in weather-conditions. This permits extremely close cooperation between the flood-forecaster and the meteorologist. The meteorological elements involved in the short-range forecasts are: (1) Type of rain (local showers, warm-front rain, cold-front rain); (2) areal extent of rainfall and approximate time of beginning and ending of rainfall over the various regions of the watershed; (3) time when the highest intensities are expected (this is assumed to coincide with the cold-front passage); (4) vertical distribution of rainfall (range of intensities between low-level stations and mountain stations); (5) variations in temperature and height of zero-isotherm--this is an important item on the West Coast since the zero-isotherm is the upper limit of a watershed from which to expect runoff either due to rain or melting snow and the portion of the watershed above the zero-isotherm will not contribute to runoff; (6) the average rainfall-intensities to be expected are also forecast--this can be done by comparing the expected storm in terms of a past storm with similar characteristics.

The above information is used by the engineer department in regulating the flood-control works. Where these basins are also used for irrigation and for other purposes, extreme care must be exercised in releasing water stored from previous rains in order to have sufficient storage-capacity available for an approaching storm. At the end of the rainy season full reservoirs are desired in order to have the greatest possible water-supply for the dry season. For this reason the forecasts become of increasing importance as the rainy season progresses.

The second part of the forecast (b) is a long-range outlook. This consists of the general weather-descriptions for a period of two to four days in advance. Special emphasis is of course put on the possibility of flood-producing precipitation. Since these forecasts are issued twice daily during the rainy season, the long-range outlook is adjusted as quickly as current data give indications of change. This forecast is used in starting water-releases prior to a storm. As subsequent forecasts confirm or disprove the earlier ones, more or less water is released.

In Southern California the flood-producing storms can usually be detected a considerable distance offshore. The development of these storms and the intensity of the circulation in the immediate vicinity of the storm-centers are the principal activities to be foreseen. The air-masses involved and their characteristics are next in importance. A knowledge of the local topography and the effect on each type of storm is essential to obtain good results.

From this general summary it is apparent that the forecasting of storm-rainfall must be a specialized type of forecasting service, designed to meet special needs. Special services for horticultural frost-protection, forest-fire weather-services, and aviation weather-services have been developed as special branches of the regular more general forecasting programs. The need has now arisen for meteorological participation in all flood-forecasting services.

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THE MATHEMATICAL SYNTHESIS OF THE FLOOD-HYDROGRAPH

R. T. Zoch

Introduction

This paper discusses how equations may be selected, or derived, which can be used to represent an observed flood-hydrograph.

Finding equations to represent observed stream-flow hydrographs is a problem which can be approached in two ways. These two approaches are radically different. One approach is that which might be called "curve-fitting." The other is that of the mathematical physicist.

This paper first explains the differences between these two approaches. Next it explains the underlying ideas and observational facts from which, it is believed, the complete solution of the most general case of the stream-flow hydrograph eventually can be obtained in the sense of mathematical physics.

Complete solutions of the more general cases have not yet been obtained. However, complete solutions of special cases have been made, and the later parts of this paper explain some of the characteristics of these simpler cases.

Curve-fitting

In fitting a mathematical curve to observed data, there are two definite steps: The first is the selection of a curve, and the second is to determine the numerical values of the constants in the curve which has been selected. In the problem of curve-fitting, the selection of the curve plays an important part in obtaining a good fit, while the determination of the constants is merely work of routine computation. Only the first step is discussed here.

To select a curve, empirical methods may be used. When these empirical methods are used, the constants of the curve chosen have no physical meaning. Generally speaking, the more constants used, the more likely a good fit will result; indeed a perfect fit must result if the number of constants equals the number of observations. If a very good fit is obtained with only a few constants, the curve may be of great practical value, but it is generally unsatisfying, because no physical meaning is attached to any one constant.

Another way of selecting a curve is to study the underlying causes of the phenomena involved and make such assumptions that will insure that each constant has a physical meaning; then deduce the curve mathematically from these assumptions. When this method of selecting a curve is used, the actual processes involved closely resemble the processes used by the mathematical physicist. But the selection of a curve can properly be called the work of the mathematical physicist only when the basic assumptions can be connected with observations by means of induction.

When empirical methods are used to select a curve, the curve-fitter is not interested in giving a physical explanation of stream-flow or the shape of the flood-hydrograph and related phenomena; he is interested solely in getting a good fit. He is not interested in explaining in a physical sense why he may get a good fit.

When the curve-fitter uses the other method and gives to each constant a physical meaning,

he realizes that a good fit will not then be obtained unless his assumptions are close approximations to the real physical phenomena.

Mathematical physics

The aim of the mathematical physicist is to express effects as mathematical functions of their causes. The attitude of the mathematical physicist is that in the case of inanimate phenomena like causes invariably produce like results, and every physical phenomenon necessarily is a consequence of a previous cause or set of causes. The relation between cause and effect is so precise it can always be expressed quantitatively by means of mathematical functions. The work of the mathematical physicist is deriving mathematical functions which express the precise relationship between causes and the effects which they produce.

In carrying out his work, the mathematical physicist first studies observations and from them tries to find some underlying principle. This process is induction. Secondly, this underlying principle is formulated mathematically and then used as a starting point to derive equations to express every phase of the phenomena in question.

Consider, briefly, some of the past attainments of applied mathematics as a guide to what might be achieved in the synthesis of the flood-hydrograph.

One of the outstanding achievements of mathematics is in the field of celestial mechanics. By means of mathematics it is possible to predict the motions of the planets and their satellites with remarkable precision for a very long time in the future. Undoubtedly, celestial mechanics is the most remarkable achievement of applied mathematics, and it sets a standard for other sciences to attain, if such be possible. Indeed, it is the model for other sciences to emulate. In the physics laboratory, where the conditions are subject to complete control, experiments can be carried out and their results observed with great exactness; therefore, in this field the mathematical physicist has succeeded in expressing numerous effects as functions of their causes.

In the field of geophysics, the prediction of tides is very accurate, although still in large part empirical. It hardly can be compared with mathematical physics, but nevertheless it is in fact the most accurate of all human predictions of natural phenomena other than the astronomical, just mentioned. The exactness of the prediction of tides is a challenge to the other branches of geophysics.

Can the mechanical physicist be of help in predicting stream-flow? It is well known that when it rains over a river-basin some kind of a rise in the stream results. The attitude of the mathematical physicist is that, if all the causes concerning the rain and the condition of the watershed at the beginning of the rain were known, it ought to be possible, solely by means of mathematical principles logically applied, to express the resultant river-flow as a mathematical function of the time and these causes and conditions, and, moreover, that if these causes and conditions can be measured quantitatively, it should be possible to express the rise in the stream with corresponding accuracy.

Clearly, attempting to use mathematics in this problem is worth the effort. From the physical point of view its success will depend on whether underlying principles can be found from the existing observations. Even if this is accomplished, success will further depend on overcoming whatever purely mathematical difficulties may be encountered. Finally from a practical point of view the successful application of the theoretical work will naturally depend on whether the conditions of rainfall and soil can be accurately measured. It is recognized that the exact relationship existing may be such that a small error in measuring the conditions of rainfall or soil might produce a very large error in the resulting stream-flow.

Partial success, however, will be but a challenge to make further efforts, and, once having accomplished a certain success in the solution of the problem of expressing stream-flow as a mathematical function of the antecedent rainfall and conditions of the watershed at the time of the rainfall, the mathematical physicist will not be content until this problem is completely solved in the sense that the stream-flow can be predicted with the greatest accuracy that measurements of the initial causes and conditions justify.

Thus in practice the three most important questions a flood-forecaster must be able to answer accurately in serving the public efficiently are: (1) When will the river first reach a height where it begins to do damage? (2) When will the river reach its flood-crest? (3) How high will this flood-crest be? Once the mathematical physicist can answer these three questions

with an accuracy with which he is satisfied, it will then be his aim to predict stream-flow at all stages with a corresponding accuracy. As a matter of fact (at least in the simpler cases so far solved), these three questions are most easily answered with precision by developing equations for the complete flood-hydrograph.

It is evident that stream-flow is influenced by many factors. First, there are the size and shape of the drainage-area itself. Second, there are the variations in the rainfall which causes the stream-flow, that is, the rate of rainfall--a variable both with time and place--and its duration, which varies only with place. The time of beginning of the rain also may vary with place, and this apart from whatever variation exists in the duration and rate. The total depth of the rain is not mentioned here, because it itself is a function of the rate of rainfall and the duration of the rain, and thus is not an independent variable. Third, is the evaporation which takes place after the rain stops. Fourth are the variables due to the condition of the soil at the beginning of the rain. Under this heading are the rate of infiltration, the depth of water necessary to bring the soil to the state of saturation, the internal capacity of the soil when it is not saturated, and the external capacity of the soil. This last variable is the ability of the soil to retain water as surface pondage. All these variables vary from place to place over the drainage-area. Finally, a fifth variable is the velocity of the water within the soil, over the ground, and in the stream-channel.

The mathematical physicist approaches a problem by first simplifying it as much as possible. In a physics laboratory, it is possible to limit the variables to only those whose effects it is desired to observe. Doing this enables the mathematical physicist to use simple equations to express the effects as functions of the causes, and it also enables him to use simple assumptions from which to derive these functions and equations by means of mathematics, and generally in terms of relatively simple equations. In nature, however, controlled experiments on a very large scale are not possible. In celestial mechanics controlled experiments are out of the question, and instead the mathematical physicist makes simplifying assumptions to make his problem tractable in its initial stages. In the development of celestial mechanics, it is first assumed that the orbits of the planets are undisturbed ellipses (two-body problem); later the theory of perturbations is developed as a simplified three-body problem; and so on.

In approaching the problem of expressing stream-flow as a function of the rainfall and the condition of the ground at the time of the rain, it is necessary to make simplifying assumptions, in order to have the mathematical treatment tractable at the beginning, and afterwards to approach reality by successively removing the restrictions. If it is assumed that (1) the drainage-area is rectangular, (2) the rate of rainfall is constant with respect to both place and time, the duration constant, and the time of beginning at the same instant over the entire drainage-area, and similarly for the time of ending, (3) the evaporation after the rain ends is zero, (4) the capacity of the soil is a constant throughout the drainage-area, and the distinction between internal drainage and surface-runoff is ignored, and (5) the velocity of the water throughout is constant, we have simplifying assumptions which reduce the problem of expressing stream-flow as a function of rainfall in its simplest form. This simplified problem has been completely solved, just the same as the two-body problem in mechanics has been completely solved.

However, this paper does not give the mathematical solution of this simplest stream-flow problem; for it the reader may consult the first reference given at the end of this article.

Definitions

It is very important when applying rigorous mathematics to any subject that there be clear and exact definitions of the phenomena being dealt with. In the problem of finding a mathematical expression for stream-flow, broadly speaking there are five terms which should be kept clearly in mind; these are runoff, rainfall, discharge, infiltration, and internal drainage. In speaking of rainfall, any one of four things may be under consideration, and a precise definition for each one of these four is necessary.

The depth of water which has fallen upon any point of the ground up to any given time (beginning, of course, with some definite time, as, for example, the beginning of the rain) is the rainfall. It is measured in inches or some other unit of length. The depth of water falling upon any point of the ground per unit of time at any given time is termed the rate of rainfall. The rate of rainfall is measured in inches per hour or some other unit of length per unit of time. Mathematically, the rate of rainfall is the first derivative of the rainfall with respect to time. In general the rainfall and the rate of rainfall vary from point to point within a watershed. The volume of water which has fallen upon a given area up to any given time is termed the volume of rainfall. The volume of rainfall is measured in mile-inches or acre-feet.

or some other unit of volume. The volume of water falling upon a given area per unit of time at any given time is the volume-rate of rainfall. It is measured in mile-inches per hour or some other unit of volume per unit of time. Mathematically, the volume-rate of rainfall is the first derivative of the volume of rainfall with respect to time.

Turning to runoff, there are four corresponding definitions. The depth of water which has run off from any point of the ground up to any given time is the runoff. The depth of water running off from any point of the ground per unit of time at any given time is the rate of runoff. The volume of water which has run off from a given area up to any given time is the volume of runoff, and fourthly the volume of water running off from a given area at any given time per unit of time is the volume-rate of runoff. These four terms involving runoff are measured in exactly the same units, respectively, as the corresponding terms relating to rainfall. Mathematically speaking, the rate of runoff is the first derivative of the runoff with respect to time and also the volume-rate of runoff is the first derivative of the volume of runoff with respect to time.

Considering now discharge, there are four terms which should be distinguished. All have to deal with the water flowing in a stream. The quantity of water flowing past a given cross-section of a stream per unit of time at any given time is the discharge. It is measured in mile-inches per hour or some other unit of volume per unit of time, for example, cubic feet per second or acre-feet per hour. The quantity of water which has flowed past a given cross-section of a stream up to any given time is the volume of discharge. The volume of discharge is measured in mile-inches or some other unit of volume. Mathematically, the discharge is the first derivative of the volume of discharge with respect to time. The discharge may be measured at any cross-section of a stream-channel, and as a cross-section is selected by moving up or downstream, the drainage-area involved changes. If the discharge be divided by the area of the drainage-basin contained above the cross-section of the stream at which the discharge is measured, the mean discharge per unit-area is obtained, and for brevity this is called the discharge per unit-area. The discharge per unit-area is measured in mile-inches per hour per square mile, or, more simply, in inches per hour. Similarly, the (mean) volume-discharge per unit-area is obtained by dividing the volume of discharge by the area of the drainage-basin, and it is measured in inches.

When rain falls upon the ground, not all of it runs off or remains upon the ground, but part of it soaks into the soil. That which soaks into the soil is infiltration, and infiltration is to soil-moisture and internal drainage as rainfall itself is to surface pondage and runoff; although this analogy cannot be carried too far. For infiltration again we have four terms. Infiltration is the depth of water which has penetrated into the soil up to any given time, measured from some fixed time, as the beginning of the rain. The rate of infiltration is the depth of water penetrating the soil per unit of time at any given time. The volume of infiltration is the volume of water which has penetrated the soil contained within a given area up to any given time. The volume-rate of infiltration is the volume of water penetrating a given area of ground per unit of time at any given time. These four terms involving infiltration are measured in the same units respectively as their corresponding terms for rainfall and runoff. Infiltration and rate of infiltration apply to points within a watershed, while volumes of infiltration and volume-rate of infiltration apply to areas.

Internal drainage, broadly speaking, is that water which initially penetrated the soil as infiltration and later appears in a stream-channel as a contribution to discharge. Here again there are four terms. The internal drainage is the depth of water which has run out from within the soil beneath a given point up to any given time. The rate of internal drainage is the depth of water running out from within the soil beneath a given point per unit of time at any given time. The volume of internal drainage is the volume of water which has run out from a given area of soil up to any given time. And, the volume-rate of internal drainage is the volume of water running out from within the soil contained within a given area per unit of time at any given time. These four quantities are measured in the same units, respectively, as their corresponding terms for rainfall, infiltration, and runoff.

We thus have 20 terms altogether, and for convenience and ready reference they are shown in Table 1.

Of the terms here enumerated, the rainfall is the most easily measured. By means of a recording rain-gage the rate of rainfall can also be measured with great accuracy, and with a sufficiently large number of rain-gages and making use of approximate integration, the other two terms relating to rainfall can be accurately computed for any given drainage-area.

Turning to stream-flow, the gage-height can be measured with great accuracy, but to obtain the discharge it is necessary to know the velocity of the water, and perhaps the accuracy of

Table 1

Term	Units in which expressed
Terms related to rainfall	
Rainfall	Inches
Rate of rainfall	Inches per hour
Volume of rainfall	Mile-inches
Volume-rate of rainfall	Mile-inches per hour
Terms related to runoff	
Runoff	Inches
Rate of runoff	Inches per hour
Volume of runoff	Mile-inches
Volume-rate of runoff	Mile-inches per hour
Terms related to discharge	
Discharge	Mile-inches per hour
Volume of discharge	Mile-inches
Discharge per unit-area	Inches per hour
Volume-discharge per unit-area	Inches
Terms related to infiltration	
Infiltration	Inches
Rate of infiltration	Inches per hour
Volume of infiltration	Mile-inches
Volume-rate of infiltration	Mile-inches per hour
Terms related to internal drainage	
Internal drainage	Inches
Rate of internal drainage	Inches per hour
Volume of internal drainage	Mile-inches
Volume-rate of internal drainage	Mile-inches per hour

these observations is not quite so good as the accuracy of an individual rain-gage. Once the discharge is known, the volume of discharge may be computed by approximate integration and the other two terms computed easily--all three with corresponding accuracy.

The runoff and infiltration have been measured, but a more refined technique is required. Besides, when measured they apply only to a type of soil exactly like that on the individual plot where the measurement is made. Extensive records of observations of runoff and infiltration are unavailable, so that generalizations which can be made from these observations are few. The principles explained in the following section are thus deduced entirely from observations of discharge, of which numerous observations are available.

Basic principles and observations

What has brought about the complete solution of the simplest form of this stream-flow problem? Practical hydrologists [see 1 under "References" at end of paper] long have observed that, if the discharge taking place at a gage-station on a stream some time after a rain has occurred (that is, the falling portion of the hydrograph) be plotted on semilogarithmic paper, the discharge observed being plotted for equal intervals of time, then the observed discharge often follows a straight line quite closely. This means that the discharge approximates very nearly a simple exponential function of the time.

There are two times during the falling portion of a stream-hydrograph when the discharge approaches a straight line on semilogarithmic paper quite closely: (1) Shortly after the peak-discharge following a rain which was sufficiently heavy to cause a relatively large runoff; or for a light rain coming near the end of a long wet spell. In this case the discharge approximates a straight line on semilogarithmic paper very closely until the beginning of the next rain within the drainage-area. (2) After a long dry spell, regardless of how irregular the rains may have been at the beginning of this spell, the hydrograph for a falling stream will very closely approximate a straight line when plotted on semilogarithmic paper. In the first case mentioned

the hydrograph, when plotted on arithmetic paper, is asymptotic to a straight line which represents the discharge at the beginning of the rain. In the second case mentioned, the hydrograph, when plotted on arithmetic paper, is asymptotic to the straight line which represents zero-discharge.

When the rising portion of the hydrograph is plotted either on arithmetic or semilogarithmic paper, its shape is much less apparent. Indeed, the falling portion of the hydrograph does not invariably follow a simple exponential curve, as the occurrence of subsequent light rains may interrupt the regular fall of the stream temporarily. Generally the rainfall varies from place to place, and the rate of rainfall varies with both place and time while it is raining. For this reason the ordinary course of light and moderate rains which in themselves are quite irregular and which are irregular with respect to the rainfall they produce within the drainage-area, causes ceaseless and irregular fluctuations in the discharge. Thus the discharge varies irregularly during most of the time, but heavy rains do cause either a flood or a rise in the stream, which appears prominently on the hydrograph. This flood-hydrograph has a somewhat characteristic rise and fall.

To find whether the observed fact that the discharge at times is a simple exponential function leads to any conclusions of significance about the rate of runoff and the rate of internal drainage, return briefly to the definitions.

Loosely speaking, the volume of discharge during a particular interval of time is equal to the sum of the volume of runoff and the volume of internal drainage during this same interval. However, this is not strictly correct; it is correct if all the water in storage, as surface pondage, as soil-moisture and in the stream-channels is exactly the same at the end of the interval of time in question as it was at the beginning. For long intervals this may be the case, but for short intervals it almost invariably is not the case. Again, if the drainage-area be very small, say an individual square mile, the volume of discharge closely approximates the sum of the volume of runoff and the volume of internal drainage for any interval of time.

Generally speaking, the discharge is not equal to the sum of the volume-rate of runoff and the volume-rate of internal drainage. For a very small drainage-area it is very nearly so, because the time required for the water to flow from where it fell as rain to the outlet is small, but for a large drainage-area this time is appreciable and varies with the distance from the outlet (gaging-station); hence the discharge very likely will be greatly different from the sum in question. Now, if the change in the volume-rate of runoff or internal drainage, respectively, with respect to time is very small, then, even though the time required for water to flow from where it fell as rain to the gage varies, the contribution of each small element of the drainage-area to the discharge will not vary appreciably with time, and in such a case the discharge is very nearly equal to the sum of the volume-rate of runoff and internal drainage, and the discharge per unit-area is very nearly equal to the sum of the rate of runoff and the rate of internal drainage.

After a long dry spell, the volume-rate of runoff is zero and also the change in the volume-rate of internal drainage with respect to time is small. Hence for such a dry spell the discharge is practically synonymous with the volume-rate of internal drainage and the discharge per unit-area is practically synonymous with the rate of internal drainage. This is one of the times when observations show that the discharge is a simple exponential function of the time. Hence the rate of internal drainage and the discharge per unit-area--in this case being practically synonymous--are simple exponential functions of the time.

Consider now the steady states. When the rate of rainfall remains strictly constant for a long while, eventually a state is reached at which the rate of rainfall, less the rate of infiltration, is exactly equal to the rate of runoff. This is the first steady state for runoff. At this time no additional water accumulates on top of the soil. Some time after the rain stops (theoretically an infinite time), the rate of runoff becomes zero, as all the water on top of the soil has disappeared. This is the second steady state of runoff. Likewise, when the rain lasts a sufficiently long time, a state is reached when the rate of infiltration exactly equals the rate of internal drainage. At this time the soil is completely saturated with water. This is the first steady state for infiltration. The second steady state for infiltration would be when there is no moisture left within the soil, which, as a result of gravity, would flow under ground to the stream. For a stream which never goes dry, this state is never reached. Also, when the rain lasts a sufficiently long time, a state is reached when the discharge is exactly equal to the volume-rate of rainfall falling upon the drainage-area. This is the first steady state for discharge, and is approached only after the first steady state for both infiltration and runoff. The second steady state for discharge is zero-discharge.

After a very wet spell, the steady state for infiltration will have been attained and the discharge accounted for by infiltration and internal drainage is constant. Hence, when rains occur after the steady state for infiltration has been reached, all fluctuations in the discharge are due to changes in the rate of runoff. Moreover, internal drainage accounts for only a small portion of the discharge following heavy rains falling upon such wet soil, and, as the discharge is a simple exponential function (for the falling hydrograph), it must mean that the volume-rate of runoff which accounts for the greater portion of the discharge in such a case is a simple exponential function. For, while on a large stream the discharge per unit-area may be considerably different from the rate of runoff at an individual point in the drainage-area, for two reasons, one reason being that the soil-capacity is not uniform within the drainage-area, the other that there is a rapid change in the rate of runoff with respect to time, for a small stream the discharge per unit-area and the rate of runoff are more nearly synonymous, and the smaller the stream the more nearly equal these two things will be. It then follows that for a small area the rate of runoff, taken any time after the rain stops, must be an exponential function of the time.

Thus, when the rate of runoff is everywhere zero, observations of discharge show that the discharge, and hence by inference the rate of internal drainage, is an exponential function of the time; also when the rate of internal drainage is constant with respect to time, observations of discharge show that the discharge, and hence by inference the rate of runoff, is an exponential function of the time. In other words, whether the discharge be due primarily to internal drainage or primarily to runoff, it is a simple exponential function of the time for the falling portion of the hydrograph. Reasoning indicates that in each case the rate of internal drainage (or rate of runoff) is a simple exponential function of the time.

Now, if this exponential function of the rate of runoff be further analyzed, it will be found that the rate of runoff is proportional to the depth of water remaining with the soil, that is to say, the rate of runoff is a constant percentage of the depth of water remaining with the soil.

There is no obvious reason why the rate of runoff is not also a constant percentage of the depth of water remaining with the soil, while it is raining, indeed always. That the rate of runoff is a constant percentage of the depth of water remaining with the soil was not long ago pointed out because the rate of runoff itself is a variable which is very difficult to measure, and, while discharge is a quantity which is more easily measured, the discharge approaches the simple exponential function only after the lapse of a certain time after the end of the rain. If the observed fact that the discharge approaches the exponential function of the time some time after the rain has stopped is accepted, it then follows that the rate of runoff at a given point within the drainage-area must be a constant percentage of the depth of water remaining with the soil.

For a general solution of the stream-flow problem, it is essential that the discharge which is due to runoff be distinguished from the discharge which is due to internal drainage. This can be done theoretically. However, for reasons of simplicity, the distinction between discharge due to runoff and discharge due to internal drainage is ignored in the simplest form of the stream-flow problem as explained above.

Character of the hydrograph (simpler cases)

That the rate of runoff is proportional to the depth of water remaining with the soil is the basic assumption on which the solution of the stream-flow problem rests. If this principle has been correctly obtained from the present observations of discharge, then the developments explained here (and published elsewhere) can properly be spoken of as mathematical physics. If this principle does not represent exactly what takes place in Nature, then these developments cannot be looked upon as mathematical physics, but rather must be regarded as curve-fitting. It does appear, however, that this assumption for all the mathematical developments can be verified (at least at certain times, that is, the falling portion of the hydrograph) from observations of discharge. Assuming this principle always to hold both during the rain and after, then the complete solution of the simplest stream-flow problem, as described above, follows the use of relatively simple mathematics.

After the rain stops the rate of runoff is a simple exponential function of the time, that is, is a constant times $e^{-t/C}$. While it is raining, the rate of runoff involves the exponential function, but not in the simplest form unless the rate of rainfall be constant. For a constant rate of rainfall the function which represents the rate of runoff during the rain is complementary to the function which represents it after the rain stops, that is, it is a constant times $(1 - e^{-t/C})$.

For a very small drainage-area, say an individual square mile, the volume-rate of runoff is practically synonymous with the discharge and the hydrograph has but two sections--a falling part after the rain stops, which is the simple exponential, and a rising part which is complementary to the falling part if the rate of rainfall is constant.

For a drainage-area whose length is appreciable, it is found that the hydrograph in this simplest case generally consists of four sections. For each one of these four sections a distinct mathematical equation is necessary to express the discharge as a function of the time, and the other factors enumerated above, which in the simplest case are assumed to be constant.

FIG. 1

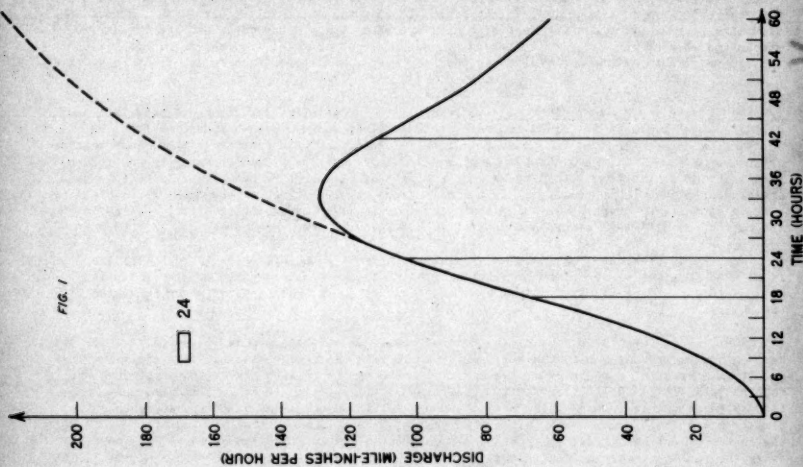
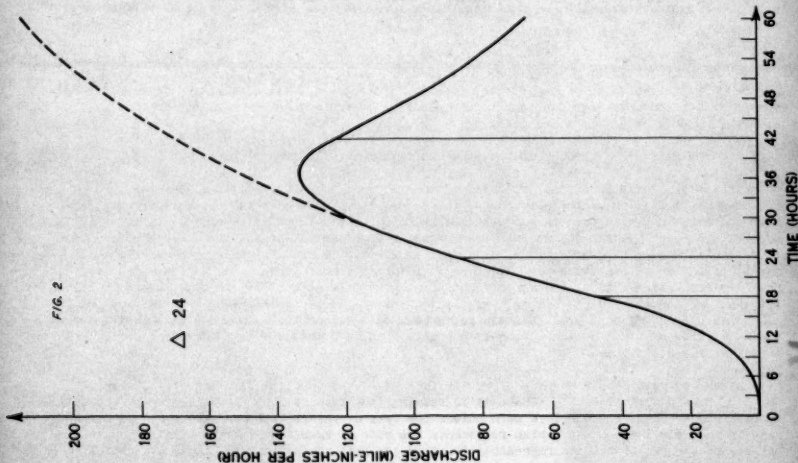


FIG. 2



To show the four sections of a stream-flow hydrograph, Figures have been constructed. These are hypothetical cases but serve to illustrate the four sections for different cases. Figure 1 is the flood-hydrograph from a rectangular drainage-area width 30 miles and length 72 miles, for a rain lasting 24 hours with a rate of rainfall of 0.125 inch per hour, with a soil-capacity at the beginning of the rain of 30 hours and with the water flowing with a velocity of four miles per hour. Figure 2 is the flood-hydrograph from a triangular drainage-area of length 72 miles, the same as in Figure 1, and an area of 2160 square miles, also the same as in Figure 1. Figures 1 and 2 thus illustrate the influence of the shape of the drainage-area on the flood-hydrograph as well as the four distinct sections of the hydrograph. The equations used in computing the hydrograph of Figure 1 are published in the Monthly Weather Review [September 1934]; equations for Figure 2 have not been published.

When the rain lasts longer than the concentration-time, the four sections of the hydrograph are as follows:

(1) A concentration-curve--The concentration-curve extends from the beginning of the rain to the concentration-time, that is, the time when the water from the source of the stream first reaches the gage. If L be the distance from the source to the gage and v be the velocity of the water in the channel--here assumed constant--then L/v is the concentration-time. During this interval of time the discharge is increasing from two causes: (a) increase in the area contributing to the discharge; (b) gradual approach of the rate of runoff to the rainfall-rate, its asymptotic limit. In Figures 1 and 2, the concentration-curve extends from 0 to 18 hours.

(2) A saturation-curve--The saturation-curve extends from the concentration-time till the rain stops. After the concentration-time, the discharge increases, but it increases only from the fact that the rate of runoff is gradually approaching the constant rate of rainfall as a limit. If the rain continues sufficiently long, the saturation-curve itself will approach a straight line as a limit, that is to say, the saturation-curve is asymptotic to a straight line, and this straight line represents the discharge at a steady state, and is the discharge that would obtain if the rain lasted long enough for the discharge to equal the volume of rate of rainfall. In Figures 1 and 2, the saturation-curve extends from 18 to 24 hours. The dashed line indicates the hydrograph which would result in the rain continued at the same rate.

(3) A transition-curve--The transition-curve extends from the end of the rain until a time equalling the sum of the concentration-time plus the duration of the rain. During this interval, the peak of the hydrograph occurs. Once the mathematical equation for the transition-curve has been derived, it can be differentiated with respect to time, and the first derivative placed equal to zero. This equation can be solved for the time of the peak of the hydrograph, and, by substituting this time for the peak in the equation for the transition-curve, itself, the peak-discharge can be found. It is thus possible to express the time of the peak of the hydrograph, as well as the maximum discharge, as functions of the drainage-area, the rate of rainfall, the velocity of the water, the capacity of the soil, and the duration of the rain, all of which in this simplest stream-flow problem are considered constants. In Figures 1 and 2 the transition-curve extends from 24 to 42 hours.

(4) A depletion-curve--The depletion-curve extends from a time equal to the sum of the concentration-time plus the duration of the rain until theoretically an infinite time later. As explained above, the depletion-curve is a simple exponential function. The coefficient of the exponential function consists of terms which involve the drainage-area, the rate of rainfall when it was raining, the duration of the rain, the velocity of the water, and the capacity of the soil, all of which are treated as constants in the simplest problem. In Figures 1 and 2 the depletion-curve extends indefinitely from 42 hours.

The first three curves are not simple exponential functions, but they do have exponential terms in them.

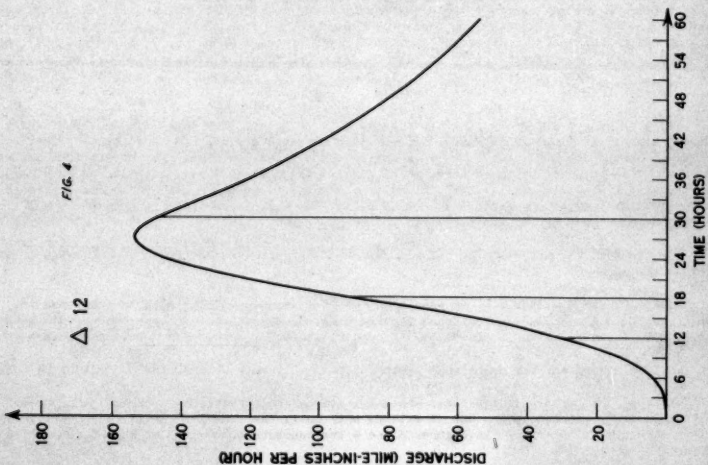
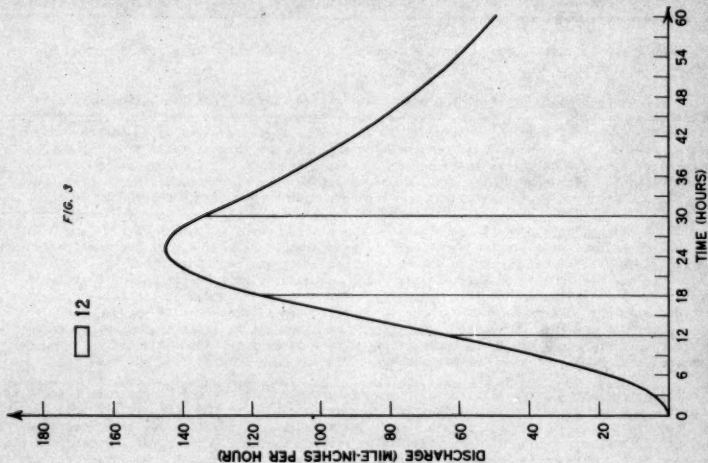
Figures 3 and 4 illustrate the condition when the duration of the rain is less than the concentration-time. The equations used in computing the hydrograph of Figure 3 are published in the Monthly Weather Review [September 1934]; equations for Figure 4 have not been published.

In this condition, the hydrograph again consists of four sections, the four sections being:

(1) The concentration-curve--This concentration-curve is represented by the same equation as that in the first condition, but it extends only until the end of the rain, an interval less than the concentration-time. In Figures 3 and 4 the concentration-curve extends from 0 to 12 hours.

(2) A curve of slow rise--This extends from the end of the rain until the concentration-time. In Figures 3 and 4 the curve of slow rise extends from 12 until 18 hours.

(3) A transition-curve--The transition-curve has here the same equation as in the first condition, but its range is different, that is to say, it extends from the concentration-time until a time equal to the sum of the duration of the rain, plus the concentration-time. This transition-curve contains the crest just as does that in condition 1, and the time of the peak of the hydrograph and the maximum discharge are represented by the same functions here as in condition 1. In Figures 3 and 4 the transition-curve extends from 18 to 30 hours.



(4) A depletion-curve--This is also a simple exponential function and agrees exactly with the equation for the depletion-curve in the first condition, both as to its range and as to its mathematical form. In Figures 3 and 4 the depletion-curve extends forward indefinitely, from 30 hours.

In computing the hypothetical hydrographs for Figures 3 and 4, the same values of the constants were used as for Figures 1 and 2 with two exceptions; these exceptions are the duration of the rain and the rate of rainfall. For Figures 3 and 4 the duration of the rain is 12 hours, one-half the value used for Figures 1 and 2. The depth of rainfall is the same for all four figures, namely, 3.00 inches. For Figures 3 and 4 the rate of rainfall is 0.250 inch per hour, twice the value used for Figures 1 and 2. It should be observed that the peak of the hydrograph for the rains of short duration (hence of greater rate of rainfall, because the depth is constant) is higher than for rains of long duration. While the rate of rainfall for Figures 3 and 4 has twice the value as for Figures 1 and 2, the peak of the hydrograph is not twice as high.

If the duration of the rain is exactly equal to the concentration-time, then the hydrograph consists of but three sections, namely, (1) the concentration-curve, (2) the transition-curve, (3) the depletion-curve.

It was stated that for very small drainage-areas the hydrograph has but two sections. There are two very special conditions when the hydrograph even for gaging-stations on streams of great length has but two sections: (1) When the duration of the rain is practically very short (theoretically zero); (2) when a storm moves downstream with a speed exactly equal to the velocity of the water in the stream. These conditions are exceptional and generally the flood-hydrograph has four sections.

Thus the mathematical synthesis of the flood-hydrograph is completely solved for the simple conditions enumerated above. It is believed that the basic principle upon which this solution depends will eventually lead to the solution of the general case.

It should be emphasized that in the simplest solution, by stating that the capacity of the soil and the velocity of the water are considered constant, it does not mean that fixed values of these quantities are necessary. It means that these quantities are constant within the particular drainage-area and for the particular rain under consideration, but for different drainage-areas and for different rains of the same drainage-area each of these two quantities can be given any value whatsoever. Also the length of the stream and the width of the drainage-area can be given any values whatsoever.

While it is recognized that the solution of this stream-flow problem in its simplest form is only an approximation to conditions found in Nature, because so many of the variables have been assumed constant within the drainage-area, it appears to be broader than any thus far obtained by empirical methods.

Further results

Naturally, it is desirable that the problem of expressing stream-flow as a function of the time and the causes which brought about any given rise in a stream be solved when the factors enumerated are not constant but have whatever values may be encountered in Nature.

By means of the concept of a histogram of a drainage-area and a drainage-area curve, the stream-flow problem has been again completely solved for a drainage-area of any shape whatsoever. Here again all the other variables are assumed constant within the drainage-area. The solution for irregularly shaped drainage-areas is not as elegant, mathematically speaking, as that for the regular drainage-areas, but it has been reduced to a case by which the discharge can be approximated to any desired degree of accuracy.

Mathematically, the solution for corrections necessary for evaporation is also complete.

When both evaporation and the irregularities of the shape of the drainage-area are considered, again the hydrograph has generally four sections. For a constant rate of rainfall, regardless of how irregular the drainage-area may be, there are again two conditions. For the first condition the duration of the rain exceeds the concentration-time, and there is one and only one flood-crest, which occurs on the transition-curve just the same as in the simplest form of the problem. For the second condition, the duration of the rain is less than the concentration-time, and the second curve of the hydrograph is not necessarily a curve of slow rise and instead is spoken of as a transition-curve of the second type; it may have any number of troughs

and crests or none at all, depending on the shape of the drainage-area; thus the principal flood-crest may precede the concentration-time.

For a variable rate of rainfall the flood-crest may precede not only the concentration-time but also the ending of the rain, depending, of course, on the way in which the rate of rainfall varies. For large drainage-areas it is practically unknown for the flood-crest to precede the ending of the rain.

The flood-hydrograph, obviously, is everywhere continuous. Moreover, it can be shown that its first derivative is everywhere continuous, even for irregularly shaped drainage-areas and varying rates of rainfall. Generally speaking, its second derivative is also continuous, though there may be a few points of discontinuity.

Since the first derivative of the hydrograph is everywhere continuous, the points which divide it into its four sections are not obvious from a glance. For a constant rate of rainfall, the point of inflection on the rising portion must come either at the concentration-time or the end of the rain, whichever is earlier, and on the falling portion the point of inflection must come at a time equal to the concentration-time plus the duration of the rain. But constant rates of rainfall are the exception in Nature and for a varying rate of rainfall the points of inflection do not necessarily come at these times.

The above explains a few of the more interesting results which are encountered in the theoretical solutions of the simpler cases.

The general case is being approached, but there still remain to be considered the variable soil-conditions and the variable velocity, each of which may turn out to be very formidable from the mathematical viewpoint. Even if success can be obtained mathematically, there yet remains the final problem of testing the mathematical equations with actual observations of observed flood-hydrographs.

References

A few references to works of practical hydrologists pointing out the exponential relation of the falling hydrograph are as follows:

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Robert E. Horton, Discussion of Committee's Report, J. New England Water-Works Ass., v. 28, p. 538 (1914).
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Otto H. Meyer, Analysis of runoff characteristics, Proc. Amer. Soc. Civ. Eng., v. 64, No. 9, p. 1772 (1938).

The following are references to theoretical papers:

- R. T. Zoch, On the relation between rainfall and streamflow, (I) Mon. Weath. Rev., v. 62, pp. 315-322 (1934), (II) Mon. Weath. Rev., v. 64, pp. 105-121 (1936), (III) Mon. Weath. Rev., v. 65, pp. 135-147 (1937).
U. S. Weather Bureau,
Washington, D. C.

ECONOMIC ASPECTS OF FLOOD-FORECASTING

Gilbert F. White

Forecasting of individual floods promotes wise human use of flood-plains in the United States in two ways. It prevents some losses which otherwise would result from floods. It is essential to the efficient operation of storage-reservoirs for flood-control. Substantial savings accrue from the present forecasting system for both purposes, but full realization of the potentialities of forecasting is hampered by lack of hydrologic data and techniques, and by lack of requisite support for making the forecast and for assuring intelligent use of the forecast.

The discussions of hydrologic data, hydrologic research, and forecasting procedures in pre-

ceding parts of this Symposium define ably the physical and technical limitations to the perfection of a national flood-forecasting system. The final limit on the accuracy and completeness of the system is economic in character. Only in so far as forecasting serves to avert losses at a cost comparing favorably with alternative means of reducing losses, and commensurate with the benefits, can it be expected to justify public financing and organization. Data on past flood-losses are generally unsatisfactory but may be used to indicate the areas in which loss reduction is of chief significance, and to segregate the types of loss most susceptible to reduction by forecasting. From these data and from the painful flood-experiences which the country recently has suffered it is possible to review the adequacy of basic economic data, and the desirability of reducing losses directly or by combining flood-forecasting with flood-control or insurance systems. From those viewpoints further improvement in forecasting is clearly warranted in favorable areas as an integral part of a national program for reduction of flood-losses.

Place of flood-forecasting in flood-plain use

Human settlement of the United States has resulted in wide-spread imperfect adjustments of land-occupancy to flood-hazard; unnecessary losses are experienced in many flood-plains; other areas have not been utilized as effectively as possible. At present the chief remedy for heavy flood-losses is flood-protection by means of reservoirs, levees, and channel-improvements. Flood protection is coming to be recognized generally, however, as only one of a number of possible measures to promote more economic use of flood-plains. The major available lines of action are the following: (1) Complete or partial protection by means of flood-control or prevention structures and land-management practices; (2) formulation and execution of plans to evacuate all or a part of the population and damageable goods in time of floods, or to reduce by other emergency-measures the deleterious effects of flood-waters without controlling them; (3) permanent readjustment in flood-plain structures to render them less vulnerable to flood-damage; (4) insurance against flood-losses; (5) permanent readjustment in flood-plain use; (6) permanent evacuation of the flood-plain. Each line of action, singly or in combination, may form the basis for maintaining a sound occupancy of some flood-plain area.

Flood-forecasting is essential to the successful operation of most storage-reservoirs and a few protective works such as the fuse-plug levees in the Lower Mississippi flood-protection plan. It is basic in any plan for emergency-evacuation. It is highly desirable in conjunction with programs for readjustment of structures or land-use. Flood-loss insurance demands effective forecasting. Complete evacuation alone among the lines of action does not include it.

The current emphasis of public agencies in the United States on the construction of flood-protection works reflects the choice of the most expedient rather than the most economical line of action in numerous areas. Generally, flood-problems have been approached with the question "Should this area be protected, or not?" Where the answer is in the affirmative and the funds and requisite public approval are provided, the appropriate works have been constructed. In most instances where the answer is negative, no systematic solution has been developed. Chiefly because of this concern with protection-works, and because those works until recent years have been of types which function without manual control or which have been designed for relatively complete protection, flood-forecasting has not been considered a major factor in the solution of the national problem. Public support for the forecasting system has been weak; scientific research on forecasting methods has been slight.

For these reasons it is impossible at this time to state the specific contributions which forecasting can or should make toward improved use of the individual flood-plains of the country. Its place in the solution can be fixed with accuracy only by evaluating the full range of available remedies in the light of local flood and land-use conditions, and then by selecting the most practicable and feasible combination of remedies. The economic problems involved in such a determination are among the more troublesome in the fields of land- and water-conservation. Comprehensive analysis of all these interlocking issues has not been made in a single flood-plain; but their significance as now viewed by investigators may be summarized in general terms.

Methods for evaluating the benefits from a given remedial measure are ill-defined. Benefits obviously comprise the losses which would be prevented in future by that measure, together with other resulting increments in the economic and social utility of the flood-plain. The bases for evaluating actual flood-losses are subject to wide range in interpretation at several points which will be stated in more detail in the succeeding sections of this paper. Resting finally on amorphous public policy with respect to the sector of the national economy affected, the interpretations by competent investigators of an identical flood-experience may yield valuations differing from each other by as much as 100 per cent. No definition of loss in all its aspects has been generally accepted. The extent to which so-called potential benefits should be appraised is a matter of controversy. No method for taking into account all relevant factors

effecting benefits--actual and potential--has demonstrated its soundness.

Methods for evaluating costs also are at issue in the arena of flood-investigations. Substantial agreement exists on the nature of costs of protection-works. The less tangible costs resulting from changes in physiographic conditions, land-use, or social structure lend themselves less readily to measurement, and often are ignored in studies of remedial measures.

As a consequence, the whole operation of comparing benefits and costs of flood-forecasting or of any other phase of flood-loss reduction is confused. A balanced appraisal of the various lines of remedial action awaits clarification of these economic problems.

Public opinion, smarting under severe lashes of flood, has not awaited the enlightenment of economics, and it has pressed for immediate action in the construction of protection-works. To the degree that forecasting is recognized as beneficial, it also will be extended by the same compelling force, and perhaps unwisely in some instances. Lacking comprehensive studies of flood-plain use, the probable quantitative significance of forecasting in the national picture can be estimated only by reference to the meager statistics on past flood-losses and to other generalized data.

Data on flood-losses

Data-collection facilities--Data on flood-losses have been collected by the Weather Bureau of the United States Department of Agriculture on a national basis since 1902 [see 9 of "References" at end of paper]. The Bureau has published estimates of the amount of damage caused by each flood, utilizing chiefly questionnaires to county agents, county and city engineers, postmasters, mayors, and river observers. Individual letters are sent to industries and railways. Officials in charge of district centers of the Weather Bureau sometimes check the returns from the questionnaires by reference to newspapers and estimates of other agencies such as the Corps of Engineers, and by occasional field-inspection.

The questionnaires now in use were introduced in 1934 and request information on losses of: (1) Tangible property totally or partially destroyed, such as buildings, fences, factories, highways, bridges, railroads, etc.; (2) farm property including (a) matured crops, (b) prospective crops, giving acreage involved, if possible, and (c) livestock and other movable property; (3) suspension of business, including wages of employees." The questionnaire also requests an estimate of "Money value of property saved by flood-warnings." These items are not defined in any more detail than given above, nor are the district centers or persons to whom the questionnaires are addressed supplied with any additional instructions for use. In 1936 and 1937 more detailed questionnaires on agricultural losses and highway losses were distributed through the Department of Agriculture's Extension Service and Bureau of Public Roads, respectively. The Weather Bureau personnel rarely make detailed inspection of flooded areas; the Bureau operates at long distance by correspondence with voluntary observers.

The other major source of damage-data are the flood-control surveys of the Corps of Engineers, United States War Department. In connection with authorized surveys for flood-control or for flood-control, irrigation, hydroelectric power and navigation, the Corps has canvassed all available data on past flood-damage in most drainage-areas of the United States, and has made independent surveys of damage after floods in those areas which experienced floods during the time that an examination, a survey, or a review of a previous survey was in progress.

The Corps does not have standard definitions of flood-loss or of survey-procedure for recording loss; responsibility for classification and evaluation of loss rests with the appropriate district engineer of the Corps. Some of its studies, such as those by the Memphis and Rock Island district offices, are outstanding for their completeness and for their innovations in technique [11 and 12]. Frequently the Corps has found it necessary to rely upon Weather Bureau records and upon old newspaper files and similar historical records for information on past losses.

The Department of Agriculture, working through the Bureau of Agricultural Economics primarily, recently has initiated flood-control surveys in which it will have need for data similar to those required by the Corps of Engineers, and under similar circumstances. A suggested procedure for collecting damage-data is in preparation by the Department but has not been released.

The Division of Disaster Relief of the American Red Cross collects and publishes statistics on the losses experienced by family or individual cases registering for emergency-aid following floods, and on the expenditures made for those cases which are aided [1]. These data are not intended to be complete, inasmuch as they exclude all losses to persons not requiring or applying for relief.

In addition to the agencies having national coverage, a few Federal, State, and local agencies collect flood-loss data in areas of restricted scope or for special types of losses. State highway-departments make inventories of damages to roads, culverts, and bridges; State health-departments canvass the damages to water-works and sewers; municipal, county, and State governments occasionally make independent estimates of losses in their respective areas; the Bureau of Agricultural Engineering examines losses in a few drainage-districts; the Bureau of Reclamation records losses to irrigation-districts and municipalities in some of the western drainage-basins; and the Tennessee Valley Authority surveys losses within the Tennessee Valley and adjacent areas.

An important step toward the unification of these data-collection services was taken recently in the issuance of a check-list of flood-losses containing definitions and suggested methods of evaluation by a committee representing interested Federal agencies and the American Society of Civil Engineers [8]. A check-list of this type should promote a uniform classification of losses, and, what is more important, an intelligent evaluation of them.

Evaluation of losses--Even though all of the data-collection work were to be correlated, the results would be unreliable and inconclusive so long as the methods of evaluation remained ill-defined and inconsistent. Most statistics on flood-losses are inadequate in one or more of four respects [13].

First, the determination of value of physical goods and property often fails to take into account obsolescence, deterioration, and future income-producing capacity in calculating the present worth of the property. Replacement-cost or original cost frequently are used for property which has nearly outworn or changed its original function. Thus, the same structure may be appraised at significantly different value by two investigators.

Second, depreciation in property value is used indiscriminately as a measure of loss to the property. If a parcel of property experiences severe damage from flood and if its value depreciates accordingly, the addition of damage to depreciation gives a value far in excess of and roughly double the actual loss.

Third, valuation of losses resulting from interruption in the production of goods and services is especially controversial. Evaluation may be made with equal propriety on any one of several assumptions with respect to the area affected (local, regional, or national), but even in those rare instances in which the assumptions are understood and stated, the methods are sometimes internally inconsistent. One investigator may exclude "business loss" entirely, another may express such losses as a percentage of the loss to goods, and a third may calculate losses of wages and value of goods in such a way as to duplicate the same loss.

Fourth, there is no generally acceptable method for evaluating losses to life, health, and social organization, factors which in some instances may be the dominant ones. Deaths are attributed to flood without careful examination of the causes, health-hazards commonly are exaggerated, and the effect of flood on the social life of a community are neglected. Data on loss of life appear to be unsatisfactory, and for that reason specific reference to them is omitted. Either because the health-hazards are low at flood-time or because public sanitation and medical care have been especially efficient, the losses to public health from floods in the United States have been slight [4]. The losses through disruption of normal social organization and activities have not been evaluated.

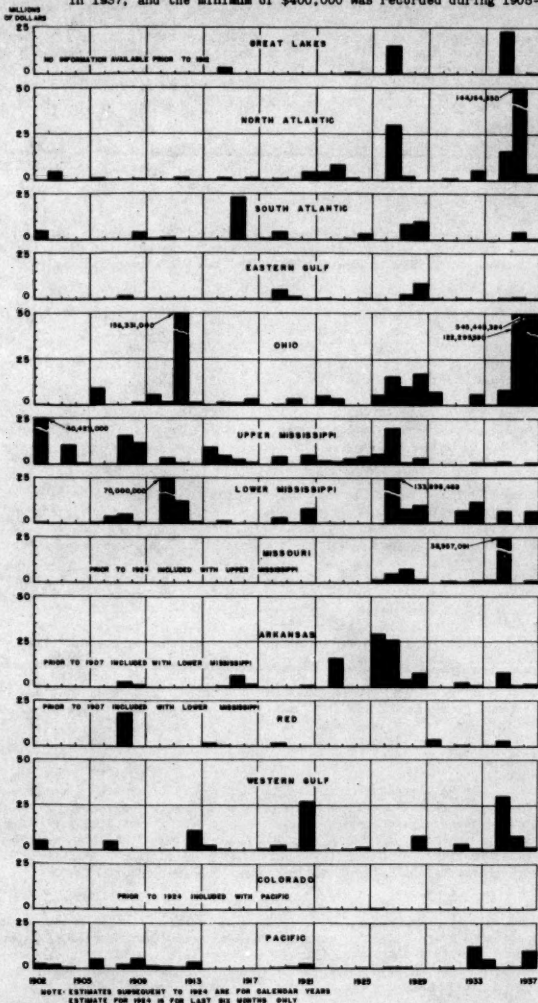
Notwithstanding several large extensions in the activities of Federal agencies in this field, the facilities for data-collection do not assure that the losses resulting from every flood will be recorded accurately, promptly, and completely. Substantial losses either are not recorded or are recorded incorrectly. Thus, the available national statistics must be used with the understanding that they are incomplete, are not strictly comparable from year to year or from place to place, and contain many gross inaccuracies in valuation of loss.

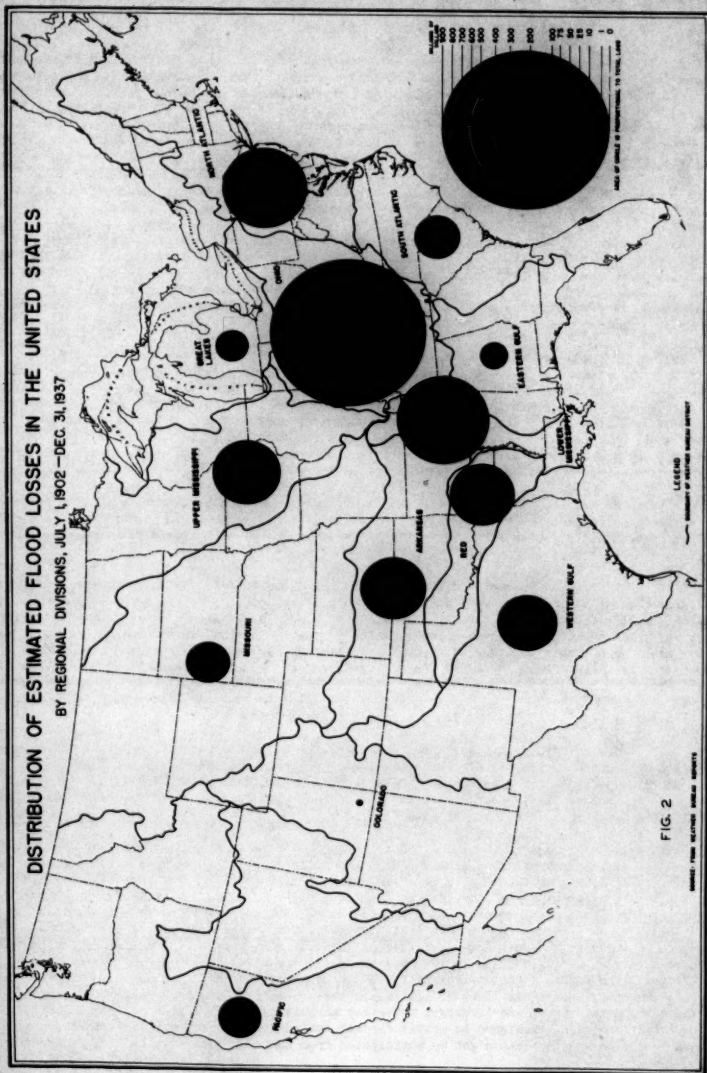
Flood-losses, 1902-1937

Although occurring in every large drainage-basin at some time and in some basin every year, flood-losses have been of outstanding significance in the North Atlantic, Ohio, and Lower Mississippi drainage-areas. During the 35-year period of record, most damage has been experienced in those areas and during five years.

According to the Weather Bureau data, a total of \$2,108,000,000 of flood-losses was experienced during the period 1902-1937. The mean annual loss as shown by these data was \$59,000,000. In recent years the Bureau has selected the period 1924-1937 for computation purposes, and has

estimated the mean annual loss at \$102,000,000. The maximum loss of \$432,000,000 was experienced in 1937, and the minimum of \$400,000 was recorded during 1905-06 (see Fig. 1).





One-fifth of all loss occurred in 1937, and approximately one-half of the total was experienced in the three years 1937, 1927, and 1936. Nearly two-thirds of the loss occurred in five of the 35 years of record (1937, 1927, 1936, 1912-13, and 1935).

The problem of the apparent increase in flood-frequency during the latter part of the record is analyzed by Mr. Jarvis in another part of this Symposium. Whether or not there has been any change in the phenomena of flood-occurrence, there unquestionably has been a marked increase in the value of property subject to flooding. The past 35 years have witnessed great changes in the extent and intensity of flood-plain use. Stream-beds in Los Angeles, California, which were unoccupied in 1902, had been subdivided and settled for residential purposes by 1937. The central business district of Pittsburgh, Pennsylvania, was built up with modern commercial buildings during that period. Encroachment rather than withdrawal has been the watchword of flood-plain users. Floods which caused little loss in numerous drainage-areas in the early part of the period would cause severe losses if they were to recur with the same magnitude today.

More than three-quarters of all loss was recorded in the North Atlantic, Ohio, Upper Mississippi, Lower Mississippi, Arkansas, Red, and West Gulf drainage-areas (see Fig. 2). In the North Atlantic, Ohio, and Upper Mississippi drainages the chief sources of loss were the urban and suburban areas bordering the streams in the generally narrow valleys of the region. This region encompasses the manufacturing belt of the United States; it is a zone of high population-density and urban concentrations.

By contrast, the losses in the Lower Mississippi, Arkansas, Red, and West Gulf drainage-areas were experienced largely in agricultural areas located in alluvial valleys. In the broad flood-plain of the Lower Mississippi, and its tributary and neighboring streams south of Cairo, the farmers and their agricultural-service communities were the flood-sufferers. To the west, Kansas City, Missouri, and Los Angeles are examples of scattered communities occupying flood-plain sites; but the total recorded losses for the entire western area and for the South Atlantic, Eastern Gulf, and Great Lakes drainages are slight by comparison with those for the manufacturing belt and the Lower Mississippi drainages.

In terms of recorded experience the problem of loss-reduction in the United States centers in the several large drainage-areas enumerated above and in a few outlying localities. Remedial measures nevertheless may involve, as in the alluvial valley of the Mississippi, programs for regulation of runoff from much larger areas.

Study of the recorded data also suggests that the reduction of losses from a few infrequent and large floods is far more significant in monetary terms than the reduction of losses from the numerous smaller floods. Some persons hold that the economic significance of relatively frequent floods of small magnitude has been underestimated in the collection of the Weather Bureau data. This contention probably is true, but from the statistics now in hand it seems unlikely that losses from the minor floods would be of sufficient volume in the aggregate to alter the record materially.

Losses directly preventable by forecasting

The losses enumerated above would have been greater had not a forecasting system been in operation during the entire period. They might have been reduced materially had that system been better supported and had there been the knowledge of weather, water, and soil which now is in hand. The quantitative importance of such reductions--past and prospective--is revealed in part by the character of the past losses.

Major classes of losses--In view of the progressive increase which encroachment has caused in the value of property and of business endangered by floods, and in view of other deficiencies in record, the losses for 1934-37 undoubtedly present a more reliable picture of the relative importance of various types of flood-damage than does the entire record. Although the losses during three of those years exceeded the mean for 1902-1937, they were the result of floods whose location and season of occurrence make them relatively representative of the national situation. Excluding the Ohio-Lower Mississippi Flood of 1937 because the estimates for that Flood were made on a different basis than the estimates for other floods during the period, it will be seen from Figure 3 that approximately 80 per cent of the estimated losses were to tangible property. About one-tenth of all losses were to matured crops. Prospective crops accounted for one-twentieth, and livestock and other movable farm-property for only one-hundredth of the total. The value assigned to losses through suspension of business (about three per cent) appears to be far smaller than might be anticipated from more detailed studies of business losses.

DISTRIBUTION OF ESTIMATED FLOOD LOSSES IN THE UNITED STATES

BY CLASS OF LOSS AND REGIONAL DIVISIONS, JAN. 1, 1934 - DEC. 31, 1937

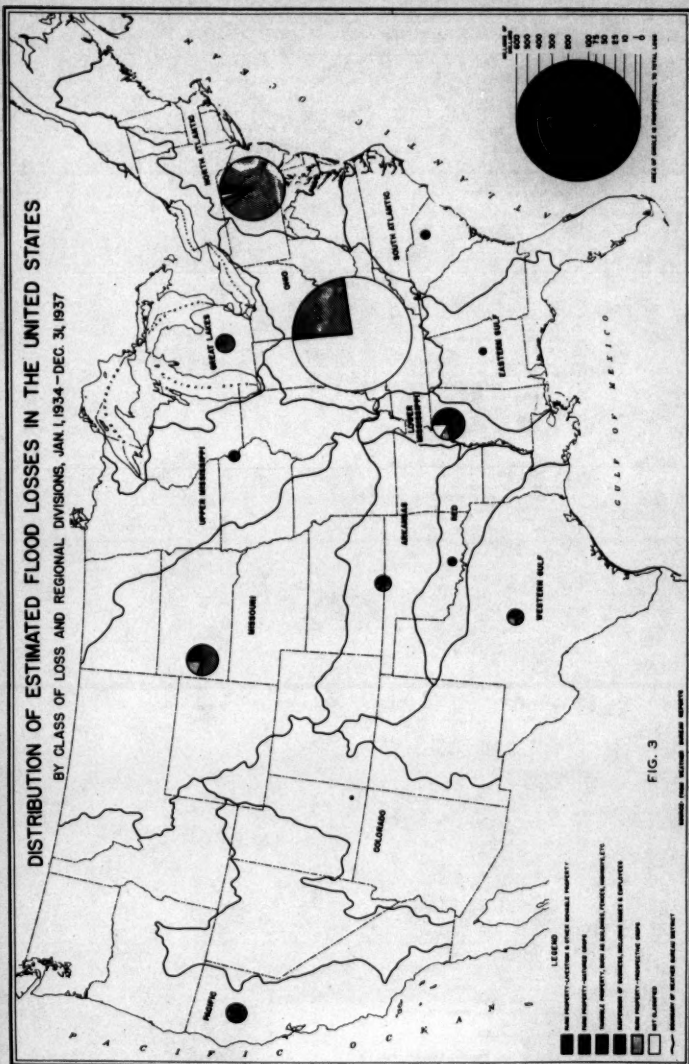


FIG. 3

Source: From *Western World in 1990*.

Table 1.--Relative susceptibility of flood-losses to reduction by emergency-measures based on flood-forecasting

Class of loss *	Degree to which loss may be reduced by emergency-measures based on timely and accurate flood- forecasts			Emergency- measures
	Large	Medium	Small or none	
Agricultural				
1. Crops				
a. Unharvested mature crops	-	x	-	Re-scheduling - Early or more rapid harvest
b. Decrease in yield	-	-	x	-
c. Reseeding perennial crops	-	-	x	-
d. Crops not planted	-	-	x	-
e. Replanting of crops	-	-	x	Re-scheduling - Delay in planting
2. Stored crops	x	-	-	Removal
3. Orchard	-	-	x	-
4. Farm timber	-	-	x	-
5. Livestock & livestock products	x	-	-	Removal
6. Residence - see "Urban Residential"				
7. Furnishings	x	-	-	Removal
8. Personal belongings	x	-	-	Removal
9. Other farm buildings	-	-	x	-
10. Farm machinery & equipment	x	-	-	Removal, Protection
11. Automobiles, trucks, wagons, boats	x	-	-	Removal
12. Fences, roads & outdoor improvements	-	-	x	-
13. Drainage & irrigation works	-	-	x	-
14. Land	-	-	x	-
15. Non-farm income	-	-	x	-
16. Evacuation & re-occupation	-	-	x	Re-scheduling
Urban Residential				
1. Residence				
a. Foundation	-	-	x	-
b. Superstructure	-	-	x	-
c. Improvements (fixed)	-	x	-	Protection
d. Decorations	-	-	x	-
2. Furnishings	x	-	-	Removal
3. Personal belongings	x	-	-	Removal
4. Garage & other buildings	-	-	x	-
5. Automobiles, wagons, trucks	x	-	-	Removal
6. Grounds & outdoor improvements	-	-	x	-
7. Loss of <u>property</u> income	-	-	x	-
8. Evacuation & re-occupation	-	-	x	-
Retail & Wholesale Commercial				
1. Building - see "Urban Residential"				
2. Furnishings	x	-	-	Removal
3. Equipment	x	-	-	Removal, protection
4. Stock of merchandise	x	-	-	Removal
5. Minor buildings	-	-	x	-
6. Automobiles, wagons, trucks, etc.	x	-	-	Removal
7. Grounds & improvements	-	-	x	-
8. Business interruption				
a. Production of goods & services	-	x	-	Re-scheduling
b. Productive equipment & supplies	-	x	-	Protection, removal, re-scheduling
c. Excess cost of delayed sales	-	-	x	-
9. Evacuation & re-occupation	-	-	x	-
Manufacturing				
1. Buildings - see "Urban Residential"				
2. Office furnishings & records	x	-	-	Removal
3. Plant machinery	-	x	-	Removal, protection
4. Stock of raw materials or finished goods	x	-	-	Removal, protection
5. Minor buildings	-	-	x	-
6. Automobiles, wagons, trucks, etc.	x	-	-	Removal
7. Grounds & improvements	-	-	x	-
8. Business interruption				
a. Production of goods	-	x	-	-
b. Productive equipment & supplies	-	x	-	-
c. Excess cost of delayed production	-	-	x	-
9. Evacuation & re-occupation	-	-	x	-
Public Buildings & Grounds				
1. Building - see "Urban Residential"				
2. Furnishings	x	-	-	Removal
3. Equipment	-	x	-	Removal, protection
4. Stocks of supplies	x	-	-	Removal
5. Public records, books or other valuables	x	-	-	Removal
6. Minor buildings	-	-	x	-
7. Grounds	-	-	x	-
8. Automobiles, wagons, trucks, etc.	x	-	-	Removal
9. Evacuation or re-occupation	-	-	x	-

Table 1--Concluded

Class of loss *	Degree to which loss may be reduced by emergency-measures based on timely and accurate flood- forecasts			Emergency- measures
	Large	Medium	Small or none	
Public Services				
1. Indoor equipment, housing & grounds	-	X	-	Protection
2. Outdoor stationary equipment	-	X	-	Protection
3. Outdoor mobile equipment	X	-	-	Removal
4. Underground facilities	-	X	-	-
5. Lines, mains, tracks, poles, etc.	-	-	X	-
6. Emergency service	X	-	-	Re-scheduling
7. Evacuation & reoccupation	-	-	X	Re-scheduling
Railroads				
1. Minor buildings	-	-	X	-
2. Outdoor stationary equipment	-	X	-	Protection
3. Roadway	-	-	X	-
4. Rolling stock	X	-	-	Removal
5. Goods in transit	X	-	-	Re-scheduling, removal
6. Emergency service	-	X	-	Re-scheduling
7. Evacuation & reoccupation	-	-	X	Re-scheduling
City Streets & Highways				
1. Roadway	-	-	X	-
2. Cost of re-routing traffic	-	X	-	Re-scheduling
3. Cost of fighting flood	-	X	-	Re-scheduling
4. Clean-up	-	-	X	-
Bridges				
1. Piers & abutments	-	X	-	Protection
2. Superstructure	-	X	-	Protection
3. Approaches	-	-	X	-
4. Utilities	-	-	X	-
Miscellaneous river structures - Dams, revetments, levees, etc.				
	-	-	X	-
Relief Expenditures				
1. Evacuation & rescue work	-	X	-	Re-scheduling
2. Emergency supplies	-	X	-	"
3. Administration on rescue camps	-	X	-	"
4. Care of sick & injured	-	X	-	"
5. Policing	-	X	-	"
6. Flood-fighting	-	X	-	"
7. Clean-up (public)	-	-	X	-
Public Health				
1. Sickness & injury	-	X	-	Re-scheduling
2. Emergency public health activities	-	X	-	"
3. Loss of life	-	X	-	Removal, reduction in rescue work, improved public health work.

* Classification from National Resources Committee, Report of the Subcommittee on Flood Damage Data, March 15, 1939, mimeographed.

As might be expected, the losses to tangible property and through suspension of business were of greater importance in the North Atlantic and Ohio basins whereas agricultural losses loomed largest in the Lower Mississippi, Red, Arkansas, and Western Gulf drainage-areas.

The Weather Bureau classifications give only a clue to the character of flood-losses as affected by forecasting. A more satisfactory understanding of them may be obtained from Table 1 and from examination of detailed reports for selected flood-plains.

Losses, as classified by the Subcommittee on Flood-Damage Data, may be grouped according to their susceptibility to reduction by emergency-measures based upon flood-forecasting. The more promising of the emergency-measures are the following:

(1) Removal--The removal of goods above the expected flood-stage by means of evacuation from the flood-zone or by their elevation in the same place. The druggist who moves his goods to the top shelves, the textile manufacturer who transports his raw materials to a higher floor in the factory, and the householder who trucks his piano out of the flood-plain are performing the same function of removal with a view to minimizing losses to movable property. This also involves the removal of people to places of safety and comfort.

(2) Protection--The treatment of immovable goods so as to render them less subject to damage from water and silt, and floating objects. This includes such measures as: The packing of engines to prevent the entrance of silt; the covering of glass windows and other fragile goods; the closure of sewer pipes and drains; and the anchoring of bridges, tanks, and similar structures which otherwise might be floated from their foundations. In effect, this comprises the application of the protective levee principle at numerous separate points (3).

(3) Re-scheduling--The readjustment in schedules of business operations so as to minimize interruption in operations. This includes: The early harvesting of crops; the re-routing of passenger and freight traffic; the orderly transfer of manufacturing, commercial, and public-utility operations to plants located outside of the flood-plains; the accumulation of supplies for homes and plants which will be isolated by flood-waters; and the notification of shippers and buyers of prospective interruption in consumption or production of the goods or services in which they are interested.

As shown schematically in Table 1, these measures may be used to reduce in large degree the losses accruing to stored crops, livestock, and livestock products, furnishings, personal belongings, movable machinery and equipment, vehicles, stocks of merchandise, office records,

Table 2--Table showing relative importance of major classes of flood-losses in three representative areas

Loss	Amount	Per cent of total	Loss	Amount	Per cent of total
Rock River, Illinois and Wisconsin, February and March, 1937 [12]			Paducah, Kentucky, Ohio River, February, 1937 [9]		
Agricultural			Urban residential		
Prospective crops	\$ 28,360	10.2	Buildings	\$ 1,861,000	14.1
Stored crops	1,445	.5	Furniture & fixtures	2,499,000	19.0
Livestock	2,000	.7	Indirect losses	140,000	1.1
Stored stocks	2,565	.9	Retail & wholesale commercial,		
Domestic buildings	58,910	21.1	Retail, hotels, banks & loan companies,		
Furniture	13,375	4.8	barber & beauty shops, laundries &		
Equipment	4,595	1.6	cleaners.		
Fences	43,245	15.5	Buildings	324,947	2.5
Drainage ditches	3,000	1.0	Furniture & fixtures	434,972	3.3
Land	4,970	1.8	Equipment	108,895	.8
Emergency work	9,533	3.4	Stock	582,337	4.4
Business suspension	14,450	5.2	Indirect losses	720,335	5.5
Industrial buildings	6,450	2.3	Wholesalers & jobbers,		
Railroads	9,926	3.5	contractors & repair shops, tobacco		
Roads & streets	18,975	6.8	rehandlers, & miscellaneous offices		
Bridges	23,340	8.4	& vacant buildings.		
Traffic delay	1,500	.5	Buildings	184,980	1.4
Miscellaneous	32,816	11.8	Furniture & fixtures	74,185	.6
Total	279,454	100.0	Equipment	92,605	.7
Arkansas River, Colorado, Kansas, Oklahoma, and Arkansas (Losses from maximum flood [11])			Stock	732,790	5.6
Agricultural			Indirect losses	230,540	1.7
Yearly crops	\$ 7,548,300	43.4	Factories		
Farm improvements	819,100	4.9	Buildings	140,530	1.1
Pasture	135,800	.8	Furniture & fixtures	26,090	.2
Land	899,400	5.4	Equipment	163,045	1.2
Rural churches & schools	19,850	.1	Stock	306,705	2.3
Urban property			Indirect losses	412,040	3.1
Residential	1,307,600	7.8	Churches & public buildings, & city streets,		
Industrial	1,018,600	6.1	sewers & water works		
Public Utilities			Buildings	455,345	3.4
Electric transmission	854,200	5.1	Furniture & fixtures	79,586	.6
Telephone & telegraph	457,100	2.7	Equipment	9,420	.1
Oil & gas	261,400	1.6	Stock	4,100	.0
Railways	1,617,350	9.7	Indirect losses	35,425	.3
Highways	1,141,850	6.9	Public services & utilities		
Miscellaneous (chiefly irrigation dams & canals)	579,400	3.5	(telephone, telegraph, electric, gas, publishing, truck, bus & railroad).		
Total	16,659,950	100.0	Buildings	170,300	1.3
			Furniture & fixtures	47,665	.4
			Equipment	482,265	3.5
			Stock	429,815	3.3
			Indirect losses	578,775	4.4
			Automobiles & trucks	700,000	5.3
			Evacuation & clean-up	1,160,000	8.8
			Total	13,167,692	100.0

Table 3--Value of property saved through flood-warnings of U. S. Weather Bureau, 1903 to 1937

Year	Value	Year	Value
1903	1,850,000	1921	1,355,900
1904	125,000	1922	12,602,800
1905	5,275,000	1923	3,134,470
1906		1924	11,710,550
1907		1925	2,209,975
1908	6,696,000	1926	2,282,615
1909	3,377,000	1927	35,761,025
1910	766,500	1928	6,099,285
1911	1,638,000	1929	17,962,334
1912	19,168,000	1930	2,172,050
1913	3,300,000	1931	520,200
1914	194,000	1932	6,099,695
1915	4,522,280	1933	8,228,309
1916	634,200	1934	1,960,331
1917	1,423,000	1935	18,120,353
1918	1,201,000	1936	49,466,415
1919	1,995,900	1937	65,051,670
1920	5,234,950	Total	302,064,807

stocks of raw materials, rolling stock, and goods in transit. They may contribute in moderate degree to minimizing losses to unharvested crops, fixed improvements, immovable machinery and equipment, production of goods and services, deterioration in productive equipment and supplies, underground utilities, re-routing of traffic, bridges, and human life. Most of the emergency-expenditures for rescue-work, evacuation, provision of emergency-service from public utilities, flood-fighting, relief, and maintenance of public health may also be reduced in moderate degree by planning of operations which would be more costly and less effective if executed without warning. The remaining losses are those which in general are not readily susceptible to prevention by emergency-measures, although under favorable circumstances they may be reduced slightly.

An accurate and timely forecast is essential to the accomplishment of any of these measures, the necessary period of the warning varying with the measures to be taken. For best results, the warning must be made and the emergency-

measures planned in terms of the probable time of arrival of the "critical stage" rather than the maximum stage. On Wheeling Island in the Ohio River, for example, large-scale removal operations are suspended when the flood exceeds three feet on the approaches of the bridges which are the life-line to the mainland, even though parts of the Island may not be flooded until several hours thereafter. Likewise, the removal of rolling stock from railroad-yards, such as those at Louisville, is limited by the time during which the necessary personnel can be assembled at the yard, since many hours before the tracks are flooded it may become impossible to call together the train-crews and yard-workmen.

The importance of accuracy in forecasting maximum stage is illustrated by two grocery stores which, located at the same elevation across the street from each other in an Ohio River town, received the same flood-warning. The stock of one store was elevated to a point slightly above the expected maximum stage. The entire stock and equipment of the second store were removed to very high ground within six hours. The anticipated crest was exceeded, the first store suffered losses of \$3000 and the second lost only the amount of \$200 required for trucking and labor.

Detailed statistics on flood-losses in one urban area and two agricultural areas are reported in Table 2. These are presented because they are representative of areas subject to flood in the United States, and because the field-surveys are believed to be accurate and thorough. Inasmuch as almost the entire city of Paducah was flooded in 1937, its losses furnish a fairly reliable sample of flood-losses in urban areas. The data from the Rock and Arkansas valleys reflect losses in agricultural areas including irrigation, dairy, and cotton farming. The losses to goods which might have been removed or protected are estimated to range from 10 to 50 per cent of the total losses. Assuming that effective emergency-measures might be developed for one-half of that property, the losses susceptible to prevention are believed to amount to roughly 5 to 25 per cent, with the larger proportions occurring in urban areas.

Estimates of savings--The published record of loss omits those potential losses which were averted because of flood-forecasts. Reasonably accurate warnings of flood on the Lower Ohio, Lower Missouri, and Lower Mississippi rivers have made possible large-scale evacuation and readjustment-programs in advance of many floods in those flood-plains. The only estimates of the magnitude of the resultant savings have been made since 1903 by Weather Bureau observers, whose reports show a total saving of \$302,064,807 during 1903-1937, and a mean annual saving of \$8,508,806 for the same period (Table 3).

Inasmuch as the estimates of savings are based solely on the information obtained by observers through correspondence and conversation, have not been checked or reviewed critically, and are not made on any uniform basis, they are of doubtful validity. They may be used nevertheless as affording some further clues to the economic significance of forecasting. During 1934-37 the savings amounted to approximately 15 per cent of the estimated losses, an estimated saving of 13 per cent of the potential loss (the term "potential loss" is used to mean estimated loss plus estimated savings). For the entire period of record, the Weather Bureau estimates that the potential losses were reduced 14 per cent.

Analysis of the susceptibility of losses to reduction by emergency-measures and of the importance of each major type of loss leads to the conclusion that approximately 15 per cent of

the mean annual flood-losses in the United States might be prevented by perfecting a system of forecasting the important floods a reasonable period in advance. These savings would amount to approximately \$6,000,000 to \$15,000,000 per annum as a minimum if past flood-experience were to be repeated. Past flood-losses will not be repeated, because (1) large-scale protection-works are being constructed or are authorized for construction in many drainage-areas and (2) encroachment upon the flood-plains continues uncontrolled in most states. These factors tend to offset each other. At present, control-works are outstripping encroachment in economic effect; but the persistence of the latter suggests that it is conservative to use past data in predicting the amount of preventable losses through forecasting. That reduction in losses would be in addition to the savings resulting from the present forecasting-system.

Forecasting combined with control

The construction of dams, levees, channel-improvements, or other works for flood-protection is increasing the value of flood-forecasting in the United States in two directions.

First, the successful operation of storage-reservoirs to reduce flood-crests is dependent in part upon the accuracy of a forecast of flow. The need for forecasts varies in accordance with the seasonability of occurrence of floods and with the relation of available storage-capacity to the size of the flow. In sections of the country where large floods occur only during well-defined seasons, drawdown in preparation for floods may be made in advance without a specific forecast, but even in those areas it may be desirable to have advance knowledge of the flood in order that storage-capacity may be used as fully as possible for other purposes before and after the floods.

In so far as new reservoirs are designed solely for detention-purposes, forecasting is of little moment; but the predominant trend, as stated by Mr. Saville, is in the direction of storage-reservoirs having multiple uses. The trend also is toward design of systems of reservoirs rather than individual reservoirs. Systems under construction or authorized for construction by the Corps of Engineers under authority of the Flood-Control Acts of 1936 and 1938 will cost more than \$450,000,000, and may be the forerunners of systems costing double that amount. These will be built principally in the Merrimack, Connecticut, Upper Susquehanna and Delaware, Ohio, Upper Mississippi, Lower Missouri, Arkansas, Red, and Lower Mississippi drainage-areas, and will affect many of the flood-plains now accounting for the major share of loss.

Second, to the extent that control- or protection-works do not afford complete protection against floods they deserve to be supplemented by a forecasting system. Oftentimes the completion of works which provide partial protection lulls the occupants of the flood-plain into a sense of false security, and, by reducing the minor, more frequent floods, mitigates against a continuing interest in emergency-evacuation plans. For economic reasons, levee-systems for the protection of agricultural lands like those in the Minnesota River Valley are not designed to withstand the infrequent, very large floods, but their overtopping may cause severe human distress and loss of property unless satisfactory warning is given. The authorized system of Upper Ohio River reservoirs for the protection of Pittsburgh will reduce the frequency and magnitude of floods but will not prevent the occurrence at some time of a flood as large as any which the City has experienced heretofore [7]. If the people of Pittsburgh were to remember this probability, the need for flood-forecasting in the Upper Ohio would be reduced substantially by the completion of the reservoir-system. There is danger, however, that concern with preparation for floods may decline in the City, and that the danger of heavy losses from the maximum flood in the future may be greater than before the system was begun, thus increasing the necessity for accurate forecasting. The authorized programs for flood-control by reservoirs in the Lower Ohio, Upper Mississippi, Missouri, White, Arkansas, and Red basins may be expected to create similar situations.

Flood-forecasting may be expected to increase in economic importance as flood-control improvements are made, except in so far as the improvements assure complete protection by means of detention-reservoirs, levees, or channel-improvement.

Forecasting combined with insurance

Flood-insurance offers a practicable means for stabilizing economic life in flood-plains in which neither complete protection nor permanent evacuation are desirable or immediately practicable. Indemnification of flood-losses is not obtainable generally in the United States and it would be difficult to establish. Requiring wide distribution of risks, long-term contracts,

and continued stimulation of interest, it probably never would be conspicuously profitable or suitable for private financing without governmental aid [5]. It has great merit nevertheless as a substitute for the haphazard system of private liquidation and public-relief subsidy by which flood-losses now are absorbed. It seems likely to develop in the United States soon or later. If and when it is organized, flood-insurance, like fire-insurance coverage, probably would require reasonable care on the part of the assured to save property by means of removal or protection. An efficient flood-insurance coverage would be contingent upon and would demand flood-forecasting and accompanying emergency-plans.

The cost of flood-forecasting

The forecast--The making of forecasts for individual floods requires an organization of personnel and facilities ranging in cost from a few cents to more than one dollar per square mile of drainage-area annually. Forecasts for the Mississippi River below Memphis are made from stage-relations upstream largely and may be obtained with a high degree of accuracy at relatively low cost inasmuch as the forecasts may be made with the aid of the regular telegraphic reports of gage-heights and precipitation, and relying upon relatively simple empirical formulae. In basins such as the Susquehanna, on the other hand, the headwaters-conditions seem to require heavy expenditures for the purposes described by Mr. Bernard in his paper. Total Federal appropriations for the skeleton system now in operation have amounted to not more than \$275,000 annually.

Supplemental measures--To the costs of the actual forecast should be added three other expenses which are necessary to its effective use--disseminating the forecast, advising on emergency-evacuation plans, and maintaining an awareness of the flood-hazard.

The ubiquitous radio set has rendered the distribution of flood-forecasts in the United States a relatively efficient operation. Radio stations and newspapers commonly carry up-to-the-minute news on flood-flows to those most concerned. The forecasting centers nevertheless are put to the expense of stemming figurative floods of inquiries as well as predicting the flood-flows. The Federal Government now bears the minimum cost of disseminating information but it does not support the other two lines of work.

A forecast is of no value unless those who receive it are prepared to act promptly and efficiently. The relief-operations in most floods are designed to care for the people who either lack the means or the foresight to care for themselves. The importance of thorough emergency-evacuation and preparation-plans has been recognized on a large scale only recently in the United States, chiefly as a result of activities of the American Red Cross. Work now is under way in many States on plans for evacuating and caring for refugees in time of flood, and for readjusting public utilities so as to provide the maximum amounts of service practicable at those times [2]. Federal agencies such as the Corps of Engineers and State agencies such as the highway-departments and the National Guard are preparing programs which will minimize public suffering and confusion. Complete community programs of that type obviously are needed for every settled flood-plain in the country. Similar plans on a less extensive scale also are needed for every residence, store, and manufacturing plant located on an unprotected or partially protected flood-plain. The methods of removing or protecting goods described in a preceding section must be understood if flood-loss is to be minimized by forecasting. Relatively few owners and operators now are fully conversant with such methods, nor is it possible to obtain information concerning those methods readily. With the exception of the efforts of the insurance companies to publicize means of preparing against fire-losses associated with floods [6], there are no systematic efforts to acquaint the public with the possibilities of this line of action. There is urgent need for advising on appropriate emergency-plans as a part of the flood-forecasting system.

Even a workable plan of large magnitude and precise detail may prove useless if the users have forgotten the parts which they are to play or, perhaps, the existence of the plan itself. Public perception of a flood-hazard becomes vague, and individual recognition of responsibility under a flood-emergency plan diminishes as time passes without a serious flood. Long floodless periods have a narcotic effect and make it incumbent upon the forecasting agency or some other agency to assume the unwelcome task of repeatedly reminding the flood-plain dwellers of their dangers. Use of the channels normally employed for disseminating the forecast, personal interviews with State and local officials, distribution of literature to schoolteachers, and erection of markers denoting the height of land and of probable flood-heights, are among the devices which might be employed in conjunction with the regular duties of making the forecast. The need is not for a far-flung public educational system; those facilities already exist in the radio, newspaper, and schools. Rather, the need is for constant stimulation of those media to insure that they serve the purpose of recalling flood-hazards and flood-emergency plans where they exist.

Inadequate forecasts--Among the more costly aspects of flood-forecasting is the inadequate forecast which fails of its purpose because it is incorrect or late. Often unavoidable because of deficient funds or imperfect techniques, the inadequate forecast may cause more loss than if there had been no forecast at all. A low forecast leads property-owners to postpone evacuation-work until too late, prevents the early initiation of emergency-work for the higher zones, and throws the whole system into disrepute so that its correct warnings are received less credulously. Although the Weather Bureau reports large savings resulting from flood-warnings during 1937, the writer is inclined to believe in the light of conversations with property-owners in the area that the net savings in the Ohio Basin would be very much less if the losses due to inadequate warnings also were to be taken into account.

Judged in terms of hydrologic performance, one inaccurate forecast among many accurate ones may seem insignificant, but in terms of economic losses, that one failure may outweigh all the successes. The few dramatic failures experienced in the United States counsel care and deliberation in the extension of forecasts from whatever enlargements may be made in the present system.

Conclusions

Flood-forecasting may play an important role in the reduction of flood-losses in most flood-plains where complete protection is infeasible or not immediately obtainable. As a basis for emergency-evacuation and protection, for operation of partial control-works, and for flood-insurance, its position of importance varies from one drainage-area to another according to the benefits from forecasting for those purposes and to the costs of the forecasting system.

Estimates of actual and potential benefits from forecasting are difficult to make because the present system for collection of flood-loss statistics is incomplete and inaccurate. Until that system is improved, the economic possibilities of forecasting as well as the economic aspects of most other means for reducing flood-losses can be appraised only roughly. A national organization for collecting flood-loss data by field-sampling and inspection should be organized. The techniques for evaluating losses should be altered to conform with the recommendations of the Subcommittee on Flood-Damage Data until they may be improved.

Using the scanty data available, it is estimated that approximately 15 per cent of the annual flood-loss could be prevented if an accurate reliable forecasting-system were in operation in the areas experiencing major damage (chiefly the North Atlantic, Ohio, and Lower Mississippi drainage-areas).

The cost of such a national system, over and above the expense of the present forecasting-facilities, has not been calculated, but, on the basis of the data in hand on costs and benefits, it is clear that expenditures far in excess of those now authorized by the Federal Government would be warranted. Complete or even partial forecasting systems would not be justified in every basin. A forecasting system where established properly should include facilities for disseminating the forecast, advising property-owners and Government officials on the best means of utilizing the forecast in preparing emergency-plans, and stimulating a continued awareness of the flood-hazards and of the available emergency-plans. Unless these supplemental measures are taken, the hydrologic operation of forecasting may fail utterly in its economic purpose of preventing flood-loss.

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